

**STRATIGRAPHY AND SEDIMENTOLOGY OF THE MIDDLE
ORDOVICIAN SINNIPEE GROUP, EASTERN WISCONSIN**

by

YONG (LUKE) SEOK CHOI

A thesis submitted in partial fulfilment of
the requirements for the degree of

**MASTER OF SCIENCE
(GEOLOGY)**

at the

UNIVERSITY OF WISCONSIN - MADISON

1995

MEM
AWO
C546
Y654

ANB9165

i

ABSTRACT

The Middle Ordovician (Champlainian) mixed carbonate/siliciclastic Ancell and Sinnipee groups in eastern Wisconsin contain ten lithofacies arranged in eleven parasequences and four sequences. Classification of the ten lithofacies is based on major skeletal components, sedimentary structures, textures, and argillaceousness. These lithofacies are interpreted to have been deposited in subtidal environments, mostly below fair-weather wave-base and above storm wave-base. The exception is laminated sandstone lithofacies of eolian origin in the St. Peter Formation.

A low-wave energy, microtidal, storm-dominated ramp model is postulated for some unusual ramp successions in the Sinnipee Group which lack near-shore shoal belts so that inner-ramp lagoonal mudstone prograded over low-energy storm-influenced mid-ramp deposits. This unusual ramp successions in the Sinnipee Group is interpreted to be caused by unusual hydraulic conditions in which incoming oceanic waves loses their energy very gradually over wide area in a broad epeiric sea.

Sequence stratigraphic models of end members siliciclastic and carbonate systems are relatively well-established, yet there has been little attention to mixed carbonate-siliciclastic sequences deposited on low-angle shelf. This work illustrates the variations from sequence to sequence, and parasequence to parasequence, of the role of depth/productivity profiles, transport of sediment offshore, dominance of heterotrophs over phototrophs or mixotroph biota, and variability in

siliciclastic influx.

Four depositional sequences are identified: the St. Peter and Platteville formations contain two sequences, and the Decorah and Galena formations contain one sequence each. The sequence boundaries correspond to identified or inferred unconformities.

Each depositional sequence shows gradual transition from a basal siliciclastic-dominated to an upper carbonate-dominated setting. The strata above the sequence boundaries are generally characterized by relatively high amounts of fine-grained siliciclastic sediments and storm beds, probably related to long-term lowering in relative sea level. An alternative but not conflicting hypothesis to explain the changes in clay content observed in the Galena Formation is changes in climate.

The Sinnipee Group carbonates have many characteristics of temperate-water carbonate deposits even though they were deposited within the tropical to subtropical belt, near the equator in the Caradocian. The Galena Formation, which corresponds to the late Caradocian, shows the typical characteristics of temperate carbonates in terms of fauna, and lack of buildups, composite grains and coated grains. However, general warmer conditions are inferred to have prevailed during deposition of the Platteville Formation based on the grain composition.

Ferruginous hardgrounds are abundant in the Sinnipee Group; in particular the Galena Formation contains numerous repetitive occurrences of hardgrounds. Although general characteristics and associated minerals in the Sinnipee Group hardgrounds are similar,

more than one process seems to be involved in the formation of individual hardgrounds with varying degrees. There seem to be chemical constraints controlling the formation of hardgrounds such as sea water chemistry including redox potential, as well as physical constraints such as base level change. Periodic change of such constraints could result in repetitive hardgrounds. The particular abundance of hardgrounds in the Galena Formation is probably related to the general cooling trend in the Late Ordovician.

ACKNOWLEDGMENTS

I am thankful for the help many people gave me. I would like to thank my advisor Toni Simo for recommending this project to me. He offered many valuable pieces of advice and helped me to keep right direction toward my goal. I would also like to thank for the additional assistance provided by many people and organizations. Financial support for this research project came from the U.W.- Madison Graduate School. I also received funding for summer fieldwork from the U.W.- Madison Department of Geology and Geophysics. The Wisconsin Geological and Natural History Survey provided topographic maps of the field area and access to the core-repository in Milwaukee. Bob Dott provided information on the structure of Wisconsin Arch and lithology of Glenwood strata. Charlie Byers kindly answered to my questions and accompanied me in the field with pleasure. I owe great debt of gratitude to David Clark for his valuable help in conodont study. I also thank Peter Drzweicki, Gary Gianinny, and Bill Raatz who spent their time discussing various aspects of sedimentology and helped me to be accustomed to American culture. Thanks to Phil Freiberg who introduced me to the outcrops in northeastern Wisconsin. I also wish to thank Dr. Yong Il Lee in Korea for his continuous encouragement.

My final acknowledgment is also most important: I thank my parents for supporting my study far from them and giving me their love.

TABLE OF CONTENTS

ABSTRACT	i
ACKNOWLEDGMENTS	iv
TABLE OF CONTENTS	v
LIST OF FIGURES	vii
LIST OF TABLES	xiv
I. INTRODUCTION	1
1. PURPOSE AND IMPORTANCE	1
2. GEOLOGICAL AGE, SETTING, AND PALEOGEOGRAPHY	4
3. PREVIOUS WORK	6
4. METHODOLOGY	11
5. FIELD AREA	15
II. LITHOSTRATIGRAPHY OF THE SINNIPEE GROUP, E. WI.	20
1. ST. PETER FORMATION	20
2. PLATTEVILLE FORMATION	25
Previous Work	25
Lithostratigraphic Description	28
3. DECORAH AND GALENA FORMATIONS	38
Previous Work	38
Lithostratigraphic Description	41
4. CONODONT STUDY	48
Introduction	48
Platteville Formation	50
Galena Formation	54
III. COMPONENTS	58
1. ORGANIC COMPONENTS	58
2. INORGANIC COMPONENTS	59
Quartz Sand Grains	59
Terrigenous Silt	60
Clay	63
Phosphate Grains	64
Intraclasts	64
Peloids	65
IV. LITHOFACIES DESCRIPTION AND INTERPRETATION	66

	vi
1. LAMINATED SANDSTONE (LS)	67
2. MASSIVE SANDSTONE (MS)	69
3. SHALE (Sh)	70
4. SANDY CARBONATE (SC)	73
5. SKELETAL WACKESTONE TO PACKSTONE (SWP)	76
6. MUDSTONE (Md)	80
7. NODULAR CARBONATE (NC)	84
8. THIN-BEDDED GRAINSTONE (TBG)	90
9. POROUS DOLOSTONE (PD)	106
10. CRINOIDAL WACKESTONE (CW)	111
11. LITHOFACIES RELATIONS	113
V. SEQUENCE STRATIGRAPHY & SEDIMENTOLOGY	118
1. INTRODUCTION	118
Parasequence and Sequence: Concepts and Definition	118
2. ANCELL AND SINNIPEE SEQUENCE STRATIGRAPHY	120
Introduction	120
Parasequence and Sequence Evolution	122
Summary	151
VI. FURTHER STUDY	155
1. LATE ORDOVICIAN CLIMATE	155
Introduction	155
Preliminary Results and Discussion	158
Summary	164
Methodology	165
2. ORIGIN OF HARDGROUNDS	165
Introduction	165
Description of the Hardgrounds	167
Preliminary Interpretation and Discussion	175
Proposed Work and Methodology	185
REFERENCES	187
APPENDIX A	201
APPENDIX B	204
APPENDIX D	299

LIST OF FIGURES

Figure No.	Description of Figures	Page No.
1	Exposures of Sinnipee Group in Wisconsin	2
2	Correlation of Cambrian/Ordovician rock units of southern and eastern Wisconsin	3
3	Middle and Late Ordovician paleogeography of the eastern half of the United States and Canada, to show the specific highland areas making up the Transcontinental Arch	5
4	Structure contour map on top of the Galena Formation and Galesville sandstone from Wisconsin and adjacent areas	7
5	Localities of measured sections	18
6	Cross section of the Platteville Formation in E. WI. along the correlation line AA'	19
7	Composite section of the Sinnipee Group in E. WI.	22
8	Field photograph showing incision of the St. Peter sandstone into the Prairie du Chien Group	24
9	Field photograph showing the massive sandstone (MS) and sandy dolostone (SC) of the Glenwood Member	24
10	General columnar section of the Platteville Group in northern Illinois	26
11	Characteristic fossils of the Platteville Group in northern Illinois	27
12	Correlation of the Platteville Formation from eastern Wisconsin to stratigraphic standard in the U. Mississippi Valley	29
13	Photographs showing the hardground on top of the Pecatonica Member	31
14	Field photograph of the Chana sub-member showing a cephalopod mold	32
15	Field photograph of the Dane sub-member showing upward thickening in bed thickness	32
16	Field photograph of the Mifflin Member showing greenish-gray color due to high content of green clay	34

17	Field photograph of the Grand Detour Member showing light purplish brown color	34
18	Field photograph of the Nachusa Member showing rough-weathered surface due to high porosity	36
19	Field photograph showing the hardground surface separating Platteville Formation from the Galena Formation	36
20	Unconformity surface on top of the Platteville Formation overlain by the Guttenberg Member of the Decorah Formation (A) or the Dunleith Member of the Galena Formation (B)	37
21	General columnar section of the Galena Group in northern Illinois	39
22	Characteristic fossils of the Galena Group in northern Illinois	40
23	Correlation of the Galena Formation from eastern Wisconsin to the stratigraphic standard in the U. Mississippi Valley	42
24	Rock slab photograph showing two amalgamated grainstone beds	44
25	Photomicrograph of a grainstone sample taken from the Guttenberg Member	44
26	Field photograph of the Ion sub-member showing gray color due to high clay content	46
27	Field photograph of the upper Dunleith sub-member showing relatively argillaceous-free lithology	46
28	Field photograph of the laminated sandstone lithofacies (LS) showing high angle cross-lamination and the overlying massive lithofacies (MS) of the Glenwood Member	68
29	Rock slab photograph of moderately sorted massive sandstone containing silicified oolitic grainstone pebbles reworked from the Prairie du Chien Group	68
30	Cores from Locality KE, Kenosha County, showing the shale lithofacies gradationally overlain by the pervasively bioturbated dolomitic sandstone in the Glenwood Member	71
31	Rock slab photograph of bioturbation mixing shale lithofacies (yellowish-green) and grainstone lithofacies (gray) in the Ion sub-member of the Galena Formation	71
32	Photomicrograph of the sandy carbonate lithofacies in the Glenwood Member	74

33	Photomicrograph of the sandy carbonate lithofacies in the Glenwood Member, showing sutured boundaries between quartz grains	74
34	Rock slab photograph of the skeletal wackestone to packstone lithofacies (Type 1) in the Pecatonica Member of the Platteville Formation, showing abundant 3-7 mm-wide <i>Chondrites</i> burrows filled with carbonate mud	77
35	Field photograph of the skeletal wackestone to packstone lithofacies (Type 1) in the Pecatonica Member of the Platteville Formation, showing a ferruginous hardground	77
36	Rock slab photograph of the lithofacies SWP (Type 2) in the Wise Lake Member of the Galena Formation, showing 3-5 mm-wide <i>Chondrites</i> burrows filled with bioclasts or carbonate mud	78
37	Field photograph of the lithofacies SWP (Type 2) in the Wise Lake Member of the Galena Formation, showing two hardground horizons (base and top of the bed) and associated <i>Thalassinoides</i> burrows	78
38	Core slab photograph of strongly bioturbated Type 2 mudstone lithofacies in the Grand Detour Member of the Platteville Formation	82
39	Rock slab photograph of non- to weakly bioturbated Type 2 mudstone lithofacies in the Grand Detour Member of the Platteville Formation	82
40	Field photograph of the lithofacies NC in the Mifflin Member of the Platteville Formation	86
41	Rock slab photograph of the lithofacies NC in the Mifflin Member of the Platteville Formation, showing carbonate nodules surrounded by argillaceous lithology	86
42	Photomicrograph of a nodule in the lithofacies NC in the Mifflin Member of the Platteville Formation	87
43	Rock slab photograph of the lithofacies NC in the Mifflin Member of the Platteville Formation	87
44	Core slab photograph of intraclastic grainstone (Type 1 TBG) in the Mifflin Member of the Platteville Formation	94
45	Core slab photograph of intraclastic grainstone (Type 1 TBG) in the Mifflin Member of the Platteville Formation, showing the relationship between the intraclasts and the underlying lithologies	94

46	Photomicrograph of intraclastic grainstone (Type 1 TBG) in the Mifflin Member of the Platteville Formation, showing sutured boundary between mudstone intraclasts	95
47	Photomicrograph of Type 1 TBG lithofacies in the Mifflin Member of the Platteville Formation, showing matrix consisting of skeletal fragments	95
48	Rock slab photograph of bioclastic grainstone (Type 2 TBG) in the Ion sub-member of the Galena Formation, consisting of pyrite-stained bioclasts and floating intraclasts	96
49	Rock slab photograph of shaly bioclastic packstone (Type 2 TBG) in the Ion sub-member of the Galena Formation	96
50	Photomicrograph of bioclastic grainstone (Type 2 TBG) in the Ion sub-member of the Galena Formation	98
51	Photomicrograph of the argillaceous bioclastic packstone (Type 2 TBG) in the Ion sub-member of the Galena Formation, showing abundant terrigenous silts	98
52	Field photograph of the bioclastic grainstone (Type 2 TBG) in the Ion sub-member of the Galena Formation, containing bored intraclasts	99
53	Field photograph of Type 3 TBG lithofacies in the Wise Lake Member of the Galena Formation, showing low-angle cross lamination (hummocky cross stratification?)	99
54	Rock slab photograph of Type 3 TBG lithofacies in the upper Dunleith sub-member	100
55	Rock slab photograph of typical Type 3 TBG lithofacies in the Wise Lake Member	100
56	Field photograph of porous dolostone lithofacies in the upper Dunleith sub-member, showing irregularly distributed vesicular pores and vuggy porosity	107
57	Photomicrograph of porous dolostone lithofacies in the upper Dunleith sub-member, showing a stylolite rich in phosphate grains and pyrite	107
58	Rock slab photograph of porous dolostone lithofacies in the upper Dunleith sub-member, showing irregularly distributed vesicular pores	108
59	Core sample taken from the upper Dunleith sub-member, locality WK-2 showing tube-like bryozoan molds	108

60	Rock slab photographs of the porous dolostone lithofacies in the upper Dunleith sub-member, showing bryozoan molds	109
61	Core slab photograph of the crinoidal wackestone lithofacies (CW) in the Dubuque Member of the Galena Formation, showing abundant dark brown argillaceous partings and crinoid fragments	112
62	Photomicrograph of the CW lithofacies in the Dubuque Member of the Galena Formation, showing abundant phosphate grains concentrated in the brown partings	112
63	Schematic diagram showing the interpreted depositional system, and relative position of the lithofacies in the carbonate-dominated setting of the Sinnipee Group	114
64	Middle to Upper Ordovician sequence stratigraphy of key sections and coastal onlap curves for North America	121
65	Composite section of the St. Peter Formation to Platteville Formation in eastern Wisconsin showing relative sea-level change, and identified parasequence and sequence boundaries.	124
66	Composite Section of the Decorah to Galena formations in eastern Wisconsin showing relative sea-level change, and identified sequence and parasequence boundaries	125
67	Ancell and Sinnipee groups sequence stratigraphy in eastern Wisconsin and correlation to coastal onlap curve for North America	126
68	Schematic cross section of sequence S1, comprising three parasequences	129
69	Composite section of sequence S1 and relative sea-level curve	130
70	Paleogeographic map of Wisconsin during early Glenwood time (P1)	132
71	Changes in sedimentation in southwestern Wisconsin during early Glenwood time (Long, 1988)	133
72	Schematic cross section of sequence S2	139
73	Composite section of sequence S2 and relative sea-level curve	140
74	Mechanisms of wave erosion and hardground development during a transgression by shoreface retreat	141

75	General carbonate lithofacies model showing trends in the distribution of chlorozoan, chloralgal, rhodalgal and molechfor sediments, according to variations in latitude, water depth and other environmental factors	160
76	Schematic north-south cross-section of modern Atlantic Ocean showing circulation of major deep water masses and hypothesized circulation in Ordovician oceans	162
77	Plain view of the hardground on top of the Platteville Formation showing the hardground stained by pyrite and oxidized products of the pyrite - hematite and limonite	169
78	Photomicrograph of a hardground showing pyrite (black) and phosphorite (yellow)	169
79	Composite Section of the Sinnipee Group in E. WI., showing curves of hardground abundance, clay content, degree of bioturbation, and interpreted paleowater-depth.	171
80	Fischer plot of the Sinnipee Group hardgrounds	173
81	Columnar section of the Sinnipee Group comparing hardgrounds with clay content, bioturbation, and storm bed abundance	174
82	Schematic diagram showing the occurrence of the minerals associated with hardgrounds	176
83	Schematic diagram illustrating origin of the Galena hardgrounds	184
B-1	Key to reading columnar sections	205
B-2	Reading Key for sedimentary structures, lithology, and grain types	206
B-3	Columnar section measured from Fort Atkinson Qr., Locality 1	207
B-4	Columnar section measured from Watertown Qr., Locality 2	211
B-5	Columnar section measured from Richwood Qr., Locality 3	214
B-6	Columnar section measured from Lowell Qr., Locality 4	215
B-7	Columnar section measured from Beaver Dam Qr., Locality 5	217
B-8	Columnar section measured from Lost Lake Qr., Locality 6	219
B-9	Columnar section measured from Spruce Qr., Locality 7	220

B-10	Columnar section measured from Buckhorn Qr., Locality 8	223
B-11	Columnar section measured from Waupun Qr., Locality 9	225
B-12	Columnar section measured from Waupun North Qr., Locality 10	228
B-13	Columnar section measured from Brandon Qr., Locality 11	230
B-14	Columnar section measured from Markesan Qr., Locality 12	232
B-15	Columnar section measured from Mackford Hill Qr., Locality 13	234
B-16	Columnar section measured from Ripon Qr., Locality 14	235
B-17	Columnar section measured from Arcade Glen, Locality 15	238
B-18	Columnar section measured from Rosandale Qr., Locality 16	240
B-19	Columnar section measured from Sun Prairie Qr., Locality 17	241
B-20	Columnar section measured from core, Locality JE	244
B-21	Columnar section measured from core, Locality WK-1	252
B-22	Columnar section measured from core, Locality WK-2	261
B-23	Columnar section measured from core, Locality WK-3	270
B-24	Columnar section measured from core, Locality RA	279
B-25	Columnar section measured from core, Locality KE	289

LIST OF TABLES

Table No.	Description of Tables	Page No.
1	Stratigraphic nomenclature applied to Sinnipee Group in southwestern Wisconsin and northern Illinois	10
2	Lithofacies summary of the upper St. Peter Sandstone and Sinnipee Group	16
3	Subdivision of Ancell and Sinnipee groups in E. WI. and major non-skeletal components of each stratigraphic unit	21
4	Identified conodont species in eastern Wisconsin	51
5	Chen's unpublished data on conodont species abundance in the Platteville Formation in southwestern Wisconsin	52
6	The number of specimens of each form species of the <i>Polyplacognathus ramosa</i> (assemblage name) showing the relative abundance in the three members of the Decorah Formation in southwestern Wisconsin	56
7	Textures and abundances of quartz grains in the Sinnipee Group in E. WI	61
8	Relative proportion of grains in the thin-bedded grainstone lithofacies in the Sinnipee Group and interpreted proximity to the paleo-shoal	91
9	Lithofacies associations and main lithologic characteristics, parasequences, and depositional sequences recognized in the Ancell and Sinnipee groups in eastern Wisconsin	123
10	Correlation between lithofacies, constituents and carbonate environments	159

I. INTRODUCTION

1. PURPOSE AND IMPORTANCE

The Middle Ordovician (Champlainian) mixed carbonate/siliciclastic Sinnipee Group in eastern Wisconsin outcrops extensively in southern and eastern Wisconsin (Fig. 1). This unit has received little previous study compared to relatively well studied upper Mississippi Valley units in southwestern Wisconsin. Therefore, the objective of this study lies in a three dimensional reconstruction of the Sinnipee Group lithostratigraphy in eastern Wisconsin and their interpretation within a sequence stratigraphic framework.

The Sinnipee Group carbonates are peculiar in that they have many characteristics of temperate-water carbonate deposits (James, 1990) even though they were located within tropical to subtropical belt near the equator in Caradocian (Late Ordovician Epoch) Age. Also, numerous hardgrounds occur repeatedly at decimeter-scale intervals particularly in the Galena Formation. Solving these problems in relation with paleoclimate/paleoceanography is the second most important objective.

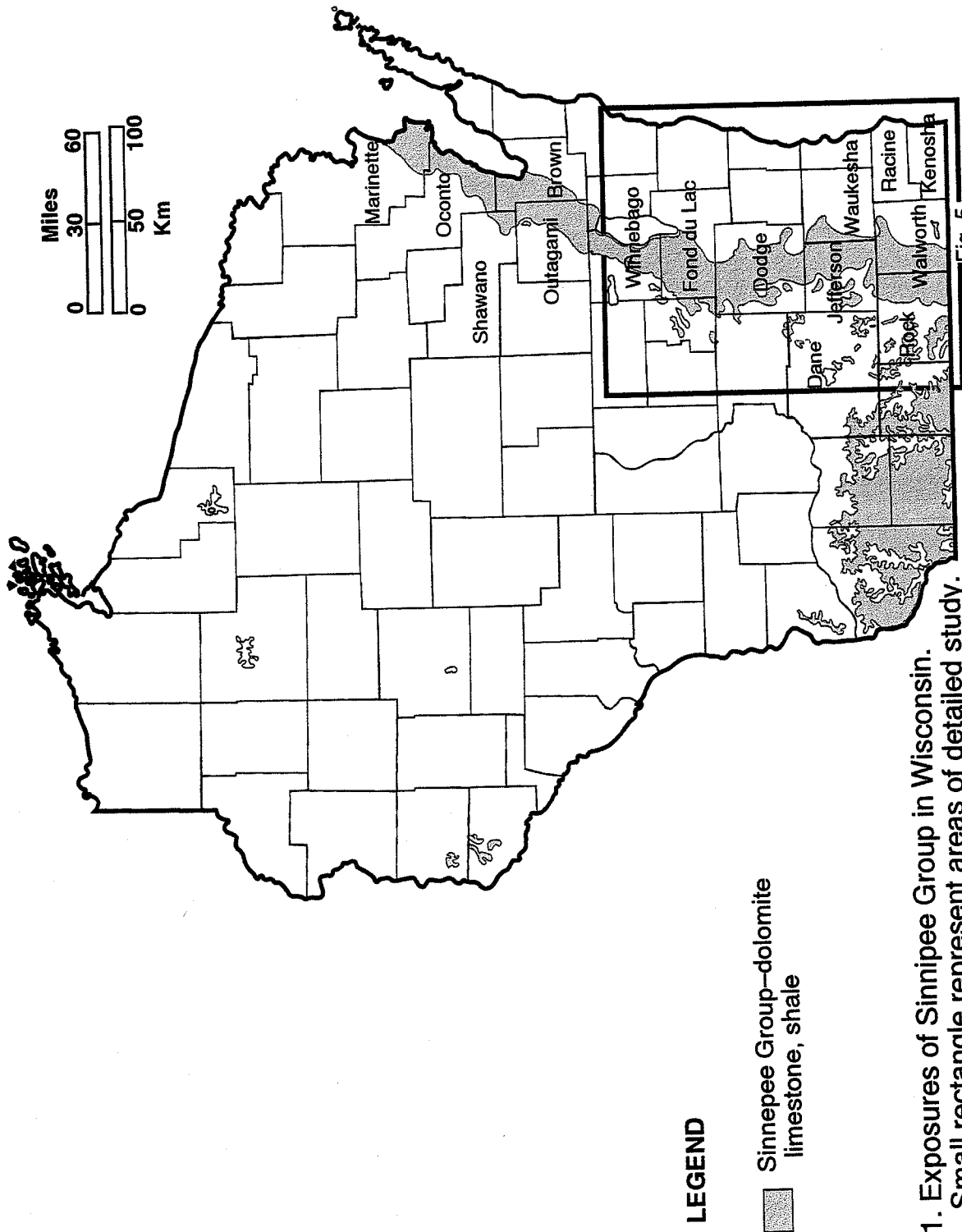


Fig. 1. Exposures of Sinnipee Group in Wisconsin. Small rectangle represent areas of detailed study.

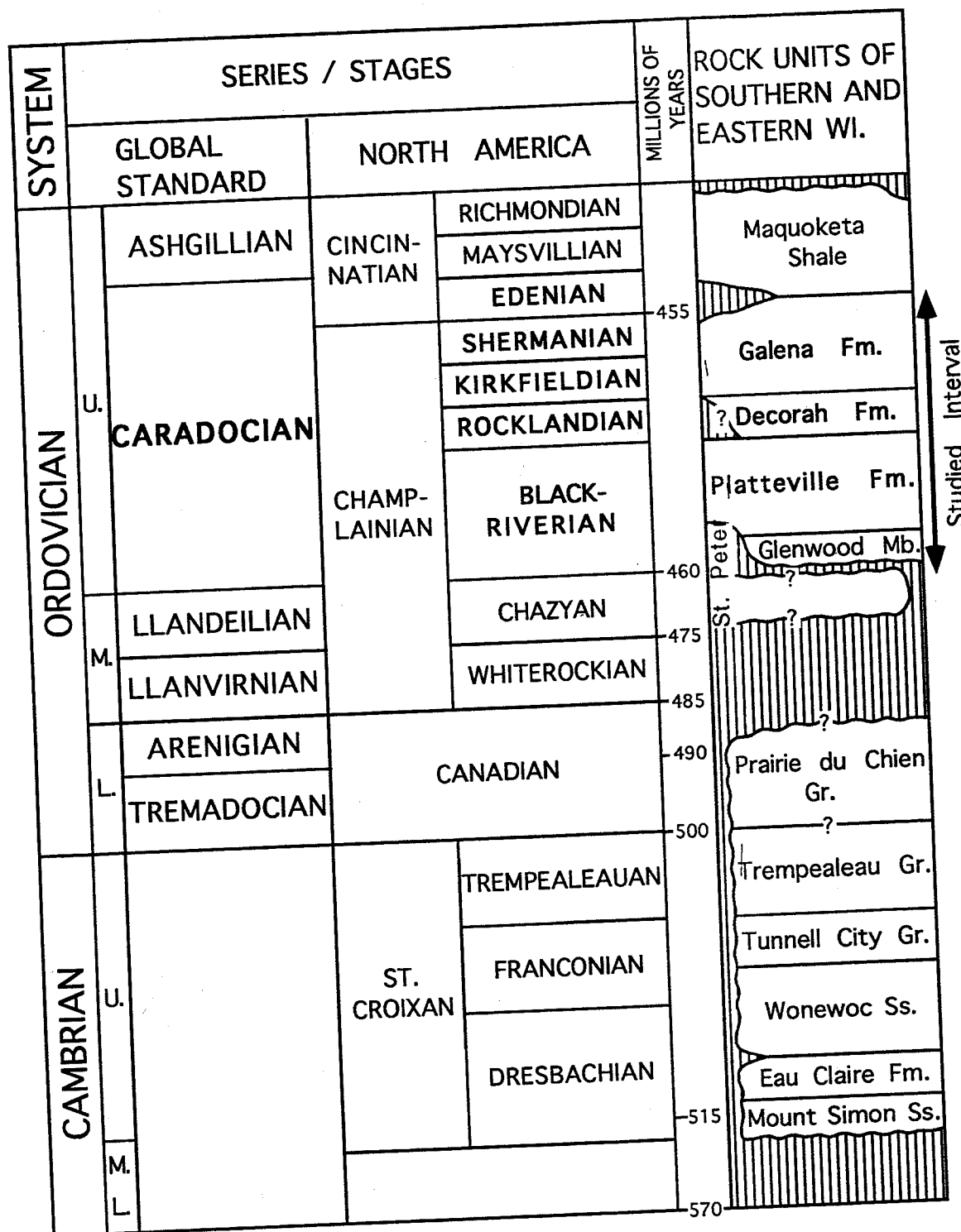


Fig. 2. Correlation of Cambrian/Ordovician rock units of southern and eastern Wisconsin; modified from Droste and Shaver (1983).

2. GEOLOGIC AGE, SETTING, AND PALEOGEOGRAPHY

The Middle Ordovician Sinnipee Group conformably overlies the St. Peter Sandstone (Middle Ordovician, Champlainian) and is unconformably overlain by the Maquoketa Shale (Upper Ordovician, Cincinnati) (Fig. 2). This unit corresponds to the Late Ordovician, Caradocian Age in the global standard, but corresponds to the Middle Ordovician chronostratigraphic unit, the Champlainian Series, in North American standard. Sinnipee Group strata and equivalent units form a thick sequence of carbonate rocks that blanket much of the Midwest. In this region, the Transcontinental Arch, Ozark Dome and Cincinnati Arch served as the major terrigenous clastic sediment source during marine deposition from Middle Ordovician-Devonian epeiric seas (Templeton and Willman, 1963; Witzke, 1980).

Following a period of erosion resulting from a global Early Ordovician sea level regression, the Middle to Upper Ordovician seas transgressed into much of the cratonic interior, accumulating the thick cratonic Tippecanoe Sequence (Sloss, 1963). As marine transgression continued and the clastic source areas were inundated, deposition of Champlainian Series sediments gradually changed from the clastic rocks of the St. Peter Sandstone to the predominantly shallow-water carbonate sediments of the Sinnipee Group (Fraser, 1976; Witzke, 1980; Fig. 3).

Overlying the St. Peter clastic rocks are the Platteville, Decorah, and Galena formations (Fig. 2). These formations comprise the Sinnipee Group and are distinguished each other by argillaceous material

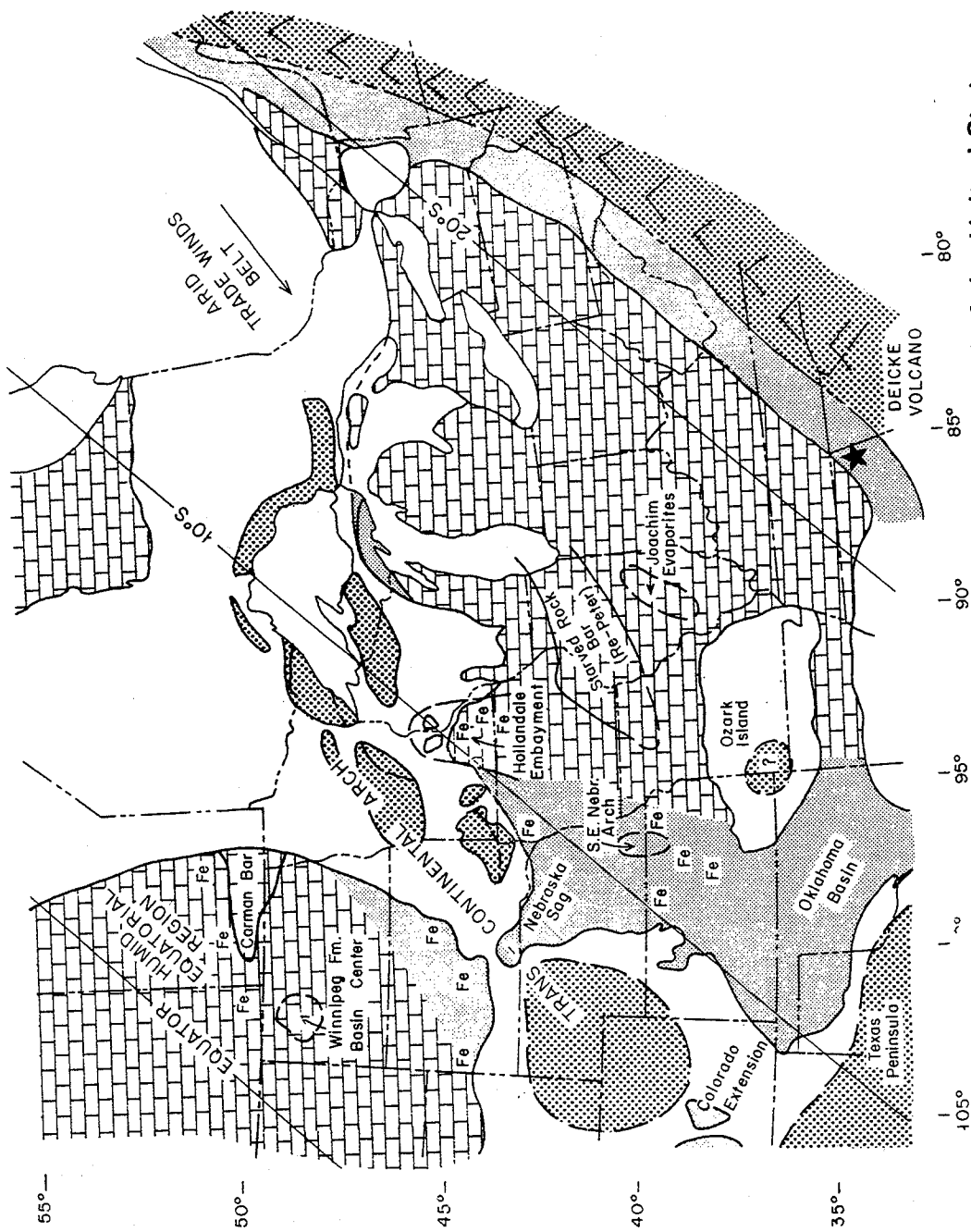


Fig. 3. Middle and Late Ordovician paleogeography of the eastern half of the United States and Canada, to show the specific highland areas making up the Transcontinenta Arch. Heavy line corresponds to present erosional edge of Middle and Late Ordovician rocks. Fe, known occurrences of oolitic hematite/goethite ironstones. Modified from Witzke (1980).

content. The oldest unit, the Platteville Formation, is argillaceous limestone/dolostone. The Decorah Formation is composed of shale and shaly carbonate. The youngest formation, the Galena Formation is relatively argillaceous-free carbonate.

Eastern Wisconsin is structurally located between the Michigan Basin and the Wisconsin Arch. This relationship is shown by a structure contour map on top of the Ordovician Galena Formation and on the Cambrian Galesville Sandstone north and west of the outcrop limits of the Galena (Fig. 4). The first major upward movement of the Wisconsin Arch occurred in Late Cambrian time, and spasmodic upheavals continued throughout Early Ordovician time, as evidenced by the sandstone units and major unconformities present in the rocks of these ages in eastern Wisconsin (Cohee, 1948).

3. PREVIOUS WORK

Middle and Late Ordovician rocks of the upper Mississippi Valley region around the mining district have been extensively studied since the 1850's (Hall, 1851; Bain, 1905; Kay, 1935; Agnew et al., 1956; Templeton and Willman, 1963; Ostrom, 1967a; Willman and Kolata, 1978; Witzke, 1980; Witzke and Kolata, 1989). The primary lithostratigraphic and biostratigraphic study was done by Agnew et al. (1946, 1956) and Ostrom (1967a). Buschbach (1964) has described the character and extent of the Platteville and Galena formations in the subsurfaces in northeastern Illinois. Conodont studies have been done for the Platteville Formation by Atkinson (1971), and for the Decorah

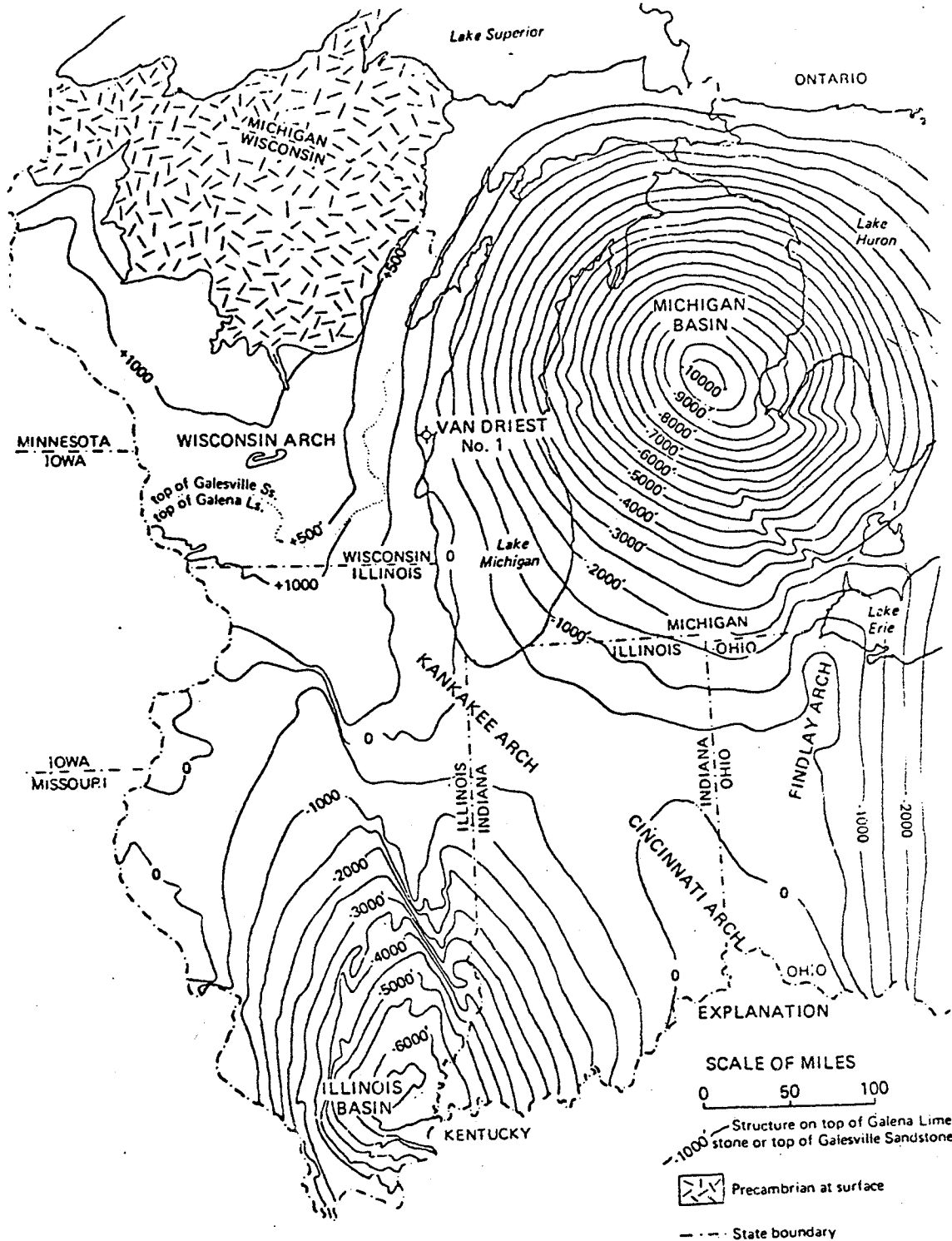


Fig. 4. Structure contour map on top of the Galena Formation and Galesville sandstone from Wisconsin and adjacent areas (Modified after Cohee et al., 1962).

and Galena formations by Clark and Babcock (1971).

Many people have worked on various aspects of the Middle Ordovician Champlainian Series particularly in the Mississippi Valley region. Many different stratigraphic names have been applied to this geological interval. In this study, Ostrom's (1967, 1969) nomenclature is used assigning the Glenwood to the uppermost member of the St. Peter Sandstone. The St. Peter Sandstone below the Glenwood Member is composed of quartz-arenite containing abundant eolian cross bedding (Winfree, 1983). The Glenwood Member comprises argillaceous sandstone, fissile green shale, and arenaceous dolostone in ascending order (Long, 1988).

Detailed study of many sections in northern Illinois by Templeton and Willman (1963) shows that the Sinnipee Group is subdivided into a number of widespread units based mainly on the relative amount of clay and silt. Small variations of the clay and silt affect the physical appearance of the strata. The argillaceous units tend to be finer grained, denser, less dolomitic, thinner bedded, weather to lighter colors, and have smoother vertical faces than the carbonate units, which are vesicular and vuggy and have rough weathered surfaces where dolomitic (Willman and Kolata, 1978).

The Platteville Formation comprises three members: Pecatonica, McGregor, and Quimbys Mill (Agnew et al., 1956). The McGregor Member is correlates to three formations in Illinois: the argillaceous Mifflin and Grand Detour, and the argillaceous-free carbonate Nachusa formations (Templeton and Willman, 1963). Same stratigraphic nomenclature is used in this study but they are regarded as members.

The Decorah Formation comprises three members: Dunleith, Wise Lake, and Dubuque. Table 1 illustrates this subdivision.

Broad paleogeographical and environmental interpretations were provided by Witzke (1980, 1987, 1990) and Witzke and Kolata (1989). Middle Ordovician paleogeography of the North American continent suggests that Middle Ordovician clastic sediments adjacent to the Transcontinental Arch were deposited in a humid equatorial belt, and carbonate deposition predominated in arid belt that included Wisconsin, southeastern Iowa, Missouri, and Illinois (Witzke, 1980, 1987; Droste and Shaver, 1983; Van der Voo, 1988; Poncet and Roux, 1990). Clastic source areas on the Transcontinental Arch were inundated, as the marine transgression continued, and a continuous sheet of carbonate sediments spread across most of the continental interior by the end of the Edenian (Witzke, 1980).

In contrast to the wealth of studies conducted on Middle Ordovician rocks in southwestern Wisconsin, little attention has been devoted to the lower Paleozoic strata in eastern Wisconsin. A major geologic investigation in eastern Wisconsin was done by Chamberlain (1877). Ostrom (1967b) constructed a geologic cross section through eastern Wisconsin using drill cuttings. Atkinson (1971) cited several exposures of the Platteville members Formation in northeastern Wisconsin recognizing the three Platteville members defined in southwestern Wisconsin. He described the conodont fauna at each location. He also compared the conodont fauna occurring in eastern Wisconsin with those of southwestern Wisconsin concluding that the Platteville Formation becomes younger in a westward direction.

GROUP	FORMATION	MEMBER	SUBDIVIDED UNITS IN NORTHERN ILLINOIS
SINNIPEE	GALENA	Dubuque Wise Lake Dunleith	
	DECORAH	Guttenberg Spechts Ferry	
		Quimbys Mill	
	PLATTEVILLE	McGregor	Nachusa Grand Detour Mifflin
		Pecatonica	
ANCELL	ST. PETER	Glenwood	

Table 1. Stratigraphic nomenclature applied to Sinnipee Group in southwestern Wisconsin and northern Illinois (Modified from Agnew et al., 1956; Templeton and Willman, 1963)

Moretti (1971) described a reference section for Paleozoic rocks in eastern Wisconsin based on a core extracted in Sheboygan County. He recognized all members of the Platteville and Decorah formations present in southern Wisconsin, but noted that the Dubuque and Wise Lake members of the Galena Formation are missing due to pre-Maquoketa erosion. LoDuca (1986) conducted a lithologic description of the Sinnipee Group in northeastern Wisconsin, and identified two formations and five members, namely, Pecatonica, McGregor, Quimbys Mill members of the Platteville Formation, and Dunleith, Wise Lake members of the Galena Formation. He recognized a general northward increase in argillaceous material content. He also suggested that the Decorah Formation is absent in this region due to facies change rather than non-deposition.

4. METHODOLOGY

17 field and 6 core locations were selected for this study from Winnebago, Fon du Lac, Dodge, Dane, Jefferson, Waukesha, Racine, and Kenosha counties (Fig. 1). Each section was measured and described in detail in terms of lithology, sedimentary structures and textures, clay content, and fossils and ichnofossils. Several outcrops of the study area to the southwest and northeast were visited for comparison and correlation. Of the measured sections, 420 samples were collected for a laboratory study. Samples were taken at noticeable changes in lithology, or at average vertical interval of 1-2 m if the lithology did not change much over that distance.

Field samples were slabbed and polished for more clear recognition of sedimentary structures and textures that are not fully or barely recognized in the field. About 90 thin sections were prepared in laboratory for recognition of component minerals, fauna, and diagenetic features.

Conodont study has been done to correlate the uppermost Platteville Formation and the lowermost strata above the Platteville Formation in eastern Wisconsin to the Sinnipee Group strata in southwestern Wisconsin. 1-3 kg Samples were taken from the uppermost unit of the Platteville Formation and lowermost unit of the Galena Formation. The samples were crushed and immersed in diluted formic acid for 24 hours to dissolve carbonate. Later, they were washed through 18 mesh and 120 mesh sieves to get finer fractions. The finer fractions were dried and immersed in heavy liquid with specific weight 2.96 to separate the heavy fraction. The heavy fractions were washed by acetone and redried. The final conodont specimens were hand-picked from the dried heavy fractions with the help of binocular microscope.

For carbonate textures, Dunham's (1962) terminology is used although most of the carbonate rocks in the study area are pervasively dolomitized, thus often original textures are hardly recognizable. The crystallinity of dolomite was expressed according to Payne crystal scale as follows:

Very coarse-crystalline	1-2 mm
Coarse-crystalline	0.5-1 mm
Medium-crystalline	0.25-0.5 mm

Fine-crystalline	0.125-0.25 mm
Very fine-crystalline	0.062-0.125 mm
Sublithographic	0.004-0.062 mm
Lithographic	< 0.004 mm

For grain size of both carbonate and siliciclastics, Wentworth size scale is used.

The thickness of beds is described as follows:

Very thin-bedded	less than 3 cm
Thin-bedded	3-10 cm
Medium-bedded	10-30 cm
Thick-bedded	30-100 cm
Very thick-bedded	> 100 cm

The term 'massive' is applied to any lithologic unit, regardless of thickness, which has no internal bedding planes.

For porosity types, Choquette and Pray's (1970) nomenclature is used. For relative intensity of bioturbation, five grades are defined from none to pervasive. For argillaceousness, also five grades are defined semi-quantitatively.

Carbonate	< 2%
Slightly argillaceous	2-5%
Moderately argillaceous	5-20%
Very argillaceous	20-50%
Shaly	> 50%

For determining approximate content of argillaceous material, the author's own experience in other project in relating the apparent argillaceousness and actual insoluble residue was used. Quartz grain

content ranging from sand to silt size was measured on thin sections under microscope by comparison with the chart for visual percentage.

After these analyses ten lithofacies were defined based on the difference in major component grains, sedimentary structures and textures, which represent specific depositional environments and processes by which they were generated (Table 2) and described in Chapter IV. All the data are plotted as stratigraphic columns to see graphically the vertical change in each measured sections (Appendix B), and as cross sections (Appendix C). The correlations are performed basically on inferred time planes although most are in reference to lithologies. Cross section of the Platteville Formation with interpretation is shown in Fig. 6.

5. FIELD AREA

The field area is located in eastern Wisconsin. Locations of detailed measured sections are shown in Fig. 5 and listed with total thickness of each section in Appendix A. Most of the outcrops are rock quarries in eastern Wisconsin some of which are still actively being mined. All six cores were extracted by Mobil Oil Corp. from southeastern counties, and they are stored in the WGNHS (Wisconsin Geological and Natural History Survey) Sample Repository (1923 East Kenilworth Place, Milwaukee) under the file number BD, with depth from ground in feet.

The measured stratigraphic interval ranges from the top of 'eolian' St. Peter sandstone beds characterized by large-scale cross-bedding to the top of the Galena Formation represented either in outcrop or in subsurface.

All specimens referenced in this thesis are in the collections of the department of Geology and Geophysics, University of Wisconsin-Madison, under file number U.W. 1896.

Table 2. Lithofacies Summary of the upper ST. Peter Sandstone and Sinnipee Group.
LS: Lithostratigraphy.

Lithofacies (Abbreviation)	Texture/Non-carbonate grains/Color	Sedimentary Structures/Bedding	Fossil/Skeletal grains by relative abundance	Bioturbation/Trace fossils	Diagenetic features/Hardgrounds	Occurrence/Facies association	Interpretation
Laminated sandstone (LS)	Fine- to medium-grained, very well sorted, well rounded quartz sandstone. Whitish yellow.	Very finely laminated within large scale cross-bedded set.	None.	Rare.	Poorly cemented.	Occurs above PDC Gp. with highly variable thickness up to 6 m.	Eolian Erg.
Massive sandstone (MS)	Medium- to coarse-grained quartz sandstone. Light yellow to greenish yellow.	Non-bedded, massive.	None.	Strong to pervasive (Skolithos, Chondrites).	Poorly cemented.	Occurs above the laminated sandstone as massive beds, 30-50 cm thick.	Upper mid-ramp below FWB.
Shale (Sh)	Dark green, fissile. Contains medium-grained quartz sandstone lenses, 2-3 cm thick.	Contains thin medium-grained sandstone lenses.	None.	Rare except in the intercalating sandstone lenses.		Occurs in the Glenwood Mb. only in Kenosha Co. Sand content increases upward.	Mid- to deep ramp.
Sandy carbonate (SC)	Originally lime mud mixed with generally more than 50% quartz grains. Moderately to poorly sorted. Generally better sorted and coarser grained upward. Light gray.	Medium-bedded.	None.	Strong to pervasive (Chondrites, Thalassinoides).	Fine- to medium-crystalline. Hardgrounds in carbonate-rich beds. south.	Occurs just below Platteville Fm. with increasing thickness to the south.	Upper mid-ramp below FWB.
Skeletal wackestone to packstone (SWP) (Type 1)	Skeletal sands of diverse fauna mixed with carbonate mud due to bioturbation. Medium- to coarse-grained, floating quartz sand grains occur in varying proportion up to 10%. Medium to dark gray.	Medium-bedded.	Crinoids, Brachiopods, Bryozoans, Trilobites.	Strong to pervasive (Chondrites, Thalassinoides).	Fine- to medium-crystalline. Hardgrounds common.	Occurs in the Chana Sub-mb. Bioclast content increase to the north.	Upper mid-ramp below FWB.
Nodular carbonate (NC)	Mudstone to packstone with abundant intercalating intraclastic grains. 1-3 cm long nodules surrounded by green to dark gray, argillaceous seams.	Very thin, irregularly bedded.	Brachiopods, Crinoids, Bryozoans, Gastropods, Trilobites.	Weak to strong (Chondrites, Thalassinoides).	Fine-crystalline. Compact. Hardgrounds common.	Occurs in the Mifflin Mb.	Mid-ramp between FWB and SWB.
Intra-bioclastic grainstone to packstone (TBG) (Type 1)	Coarse sand- to pebble-sized intraclasts and bioclast matrix.	Thin-bedded. Poorly sorted, poorly graded to normally graded.	Brachiopods, Bryozoans, Crinoids, Trilobites.	Rare to weak.	Fine- to medium-crystalline. Hardgrounds rare.	Mostly occurs in the Mifflin Mb associated with NC.	Mid-ramp storm deposits.

Table 2 (Continued).

Lithofacies (Abbreviation)	Texture/Non-carbonate grains /Color	Sedimentary Structures/ Bedding	Fossil/ Skeletal grains by relative abundance	Bioturbation/ Trace Fossils	Diagenetic features/ Hardgrounds	Occurrence/ Facies association	Interpretation
Mudstone (Md)	Slightly argillaceous to carbonate. Composed of dolomite with 0.2-1 cm thick, diffuse argillaceous seams in varying proportions. Light purplish brown to medium gray.	Thin- to medium-bedded.	Brachiopods.	Mostly weakly bioturbated except in some heavily mottled intervals (horizontal burrows).	Very fine-crystalline. Abundant chert nodules.	Occurs in the Dane Sub-mb. and in the Grand Detour Mb.	Shallow ramp, protected environment (?).
Porous dolostone (PD)	Argillaceous-free dolomite. Light brown.	Medium to thick-bedded.	Bryozoan molds abundant.	Moderate (<i>Thalassinoides?</i>).	Medium-crystalline. More abundant vesicular/vuggy porosity upward. Chert nodules common.	Occurs in the Nachusa Mb. as thick beds.	Upper mid-ramp.
Skeletal grainstone to packstone (TBG) (Type 2,3)	Grain-supported, abraded, fragmented bioclasts mostly of coarse sand size.	Thin-bedded. Some grainstone beds are normally graded and laminated, pinch and swell laterally.	Brachiopods, Bryozoans, Crinoids, Trilobites, rugose corals.	Weak to pervasive bioturbation (<i>Chondrites</i>).	Medium-to coarse-crystalline. Shelter/moldic porosities common. Hardgrounds common.	Type 2 abundant in the lower Dunleith Mb. while Type 3 common in the lower Wise Lake Mb.	Mid-ramp storm deposits below FWB.
Shale (Sh)	Green, fissile.	Very thin-bedded.	<i>Orthis</i> brachiopods common on bedding plain.	Moderate to strong.	Compaction.	Mostly occurs as mm- to cm-thick shale partings in the lower Dunleith Mb.	Mid-ramp below FWB.
Porous dolostone (PD)	Argillaceous-free dolomite. Light yellowish brown to buff.	Medium-bedded.	Brachiopods, Bryozoans, Trilobites, <i>Receptaculites</i> .	Moderate (<i>Thalassinoides?</i>).	Medium-crystalline. Abundant vesicular/vuggy hardgrounds.	Occurs mainly in the upper dunleith Mb. in SE. WI.	Upper mid-ramp.
Skeletal wackestone to packstone (SWP) (Type 2)	Sand-sized bioclasts of diverse fauna. Argillaceous to carbonate.	Medium to thick bedded.	Brachiopods, Crinoids, Trilobites, Bryozoans, rugose corals.	Densely bioturbated (<i>Chondrites</i> , <i>Thalassinoides</i>).	Fine- to medium-crystalline. Hardgrounds abundant.	Particularly common at upper Dunleith to lower Wise Lake Mb.	Mid- to deep ramp.
Fossiliferous mudstone (Md)	Slightly argillaceous to carbonate. Purplish brown.	Thin-bedded.	Gastropod (<i>Hormotoma major</i>), <i>Receptaculites</i> .	Rare to Strong bioturbation (<i>Chondrites</i>).	Very fine-crystalline.	Mainly occurs in the Wise Lake Mb.	Mid- to Deep ramp.
Crinoidal wackestone (CW)	Mudstone to wackestone with occasionally intercalating very thin packstone beds. Dark brown.	Thin-bedded (?).	Crinoids (up to Weak bioturbation 90%), <i>Chondrites</i> . Brachiopods.	Weak bioturbation (<i>Chondrites</i>).	Fine-crystalline.	Mainly occurs in the Dubuque Mb.	Lower mid-ramp.

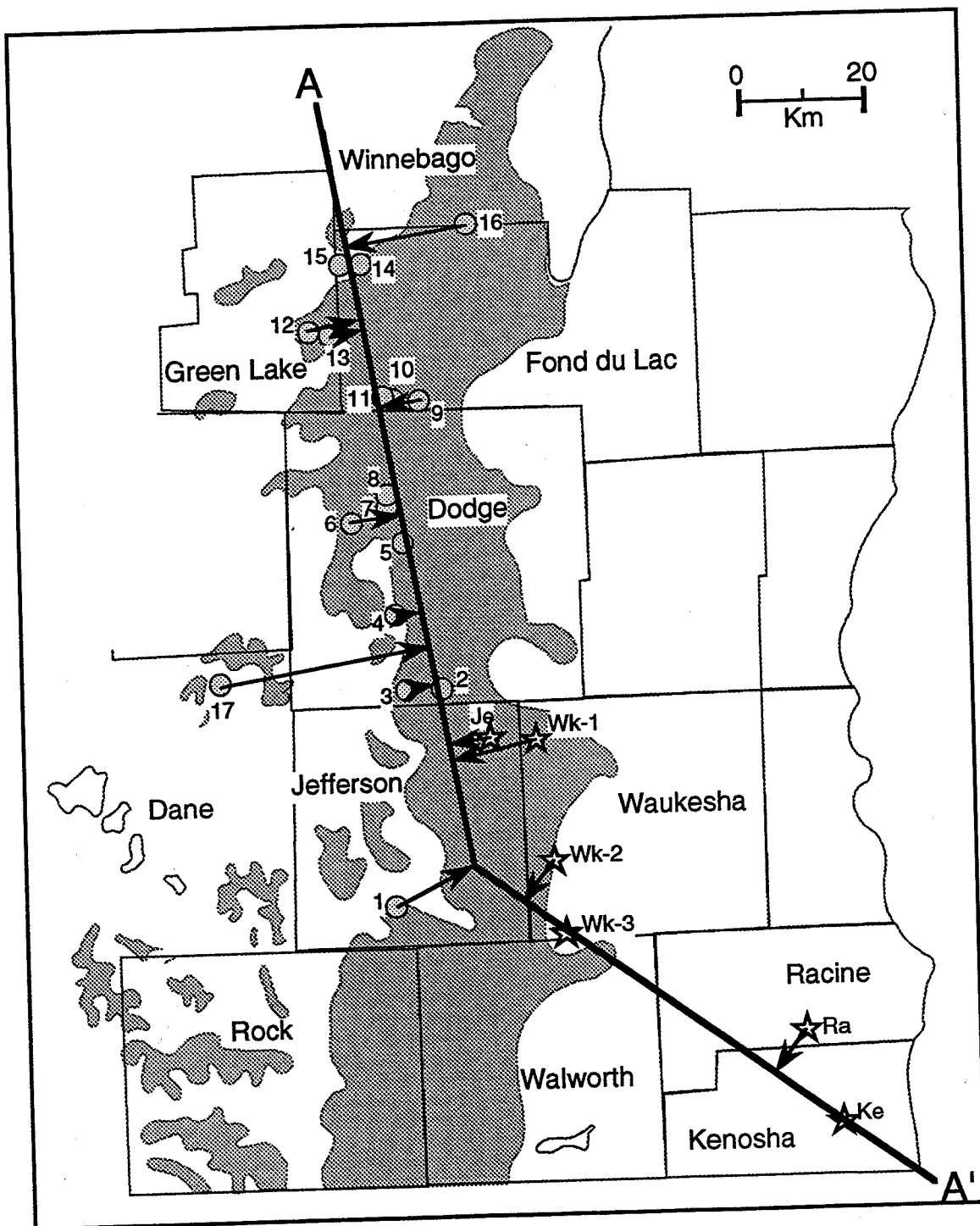


Fig. 5. Localities of measured sections. Small circles represent outcrops and stars represent core locations. Arrows represent projection of each section with 90 degrees to the correlation line A-A'. Along the line A-A', all measured sections are correlated in Appendix C and the cross section for the Platteville Formation with representative measured sections is in Fig. 6.

II. LITHOSTRATIGRAPHY OF THE ANCELL AND SINNIPEE GROUPS, E. WI.

The Middle Ordovician (Llandeilian and Caradocian Age) Ancell and Sinnipee groups in eastern Wisconsin consists mainly of sandstone, sandy carbonate, argillaceous dolostone, dolostone, and dolostone interbedded with green shale. The Ancell Group consists of the St. Peter Sandstone including Glenwood Member. The Sinnipee Group is subdivided into three formations. The lowermost formation is the Platteville which consists of four members. Decorah Formation consists of one member, and the Galena Formation consists of three members (Table 3). The recognition of the formations and members are based on relative difference in siliciclastics content, texture, bioturbation, and hardground occurrences (Fig. 7). Detailed description for each of the measured sections is provided in Appendix B.

1. ST. PETER FORMATION

The lower boundary of the Platteville Formation is observed in outcrops in Fon du Lac County, and in cores extracted from southeastern Wisconsin counties. The St. Peter Formation overlies unconformably the Prairie du Chien Group, and it is overlain by the Platteville Formation (Fig. 8).

The sandy carbonates of the Prairie du Chien Group crop out at Ripon in Fon du Lac County. They are thought to belong to the Shakopee Formation, probably the lower New Richmond Member, based on the high percentage of sandstone beds intercalated with thin green shale

FORMATION	SUBDIVIDED UNIT	LITHOFACIES	NON-SKELETALS
GALENA	Dubuque Member	CW/Md	PO ₄ , T-silt
	Wise Lake Member	Md/PD/TBG	T-silt
	Dunleith Member (upper)	PD/Md/TBG	T-silt, Int.
	Dunleith Member (lower): Ion sub-member	TBG/Sh	T-silt, Int., Q-sand
DECORAH	Guttenberg Member	TBG	PO ₄ , T-silt
PLATTEVILLE	Nachusa Member	PD/Md	
	Grand Detour Member	Md/TBG	Int., Pel.(?)
	Mifflin Member	TBG/NC	Int., Q-sand, PO ₄ , T-silt
	Pecatonia Member	Md/SWP	Q-sand, Pel.(?)
	Glenwood Member	SC/Sh/MS	Q-sand, PO ₄
ST. PETER		LS	Q-sand

Table 3. Subdivision of Ancell and Sinnipee groups in E. WI. and major non-skeletal components of each stratigraphic unit. See Table 2 for lithofacies code. Int.: intraclasts; Pel: peloids; PO₄: phosphate grains; T-silt: Terrigenous silt.

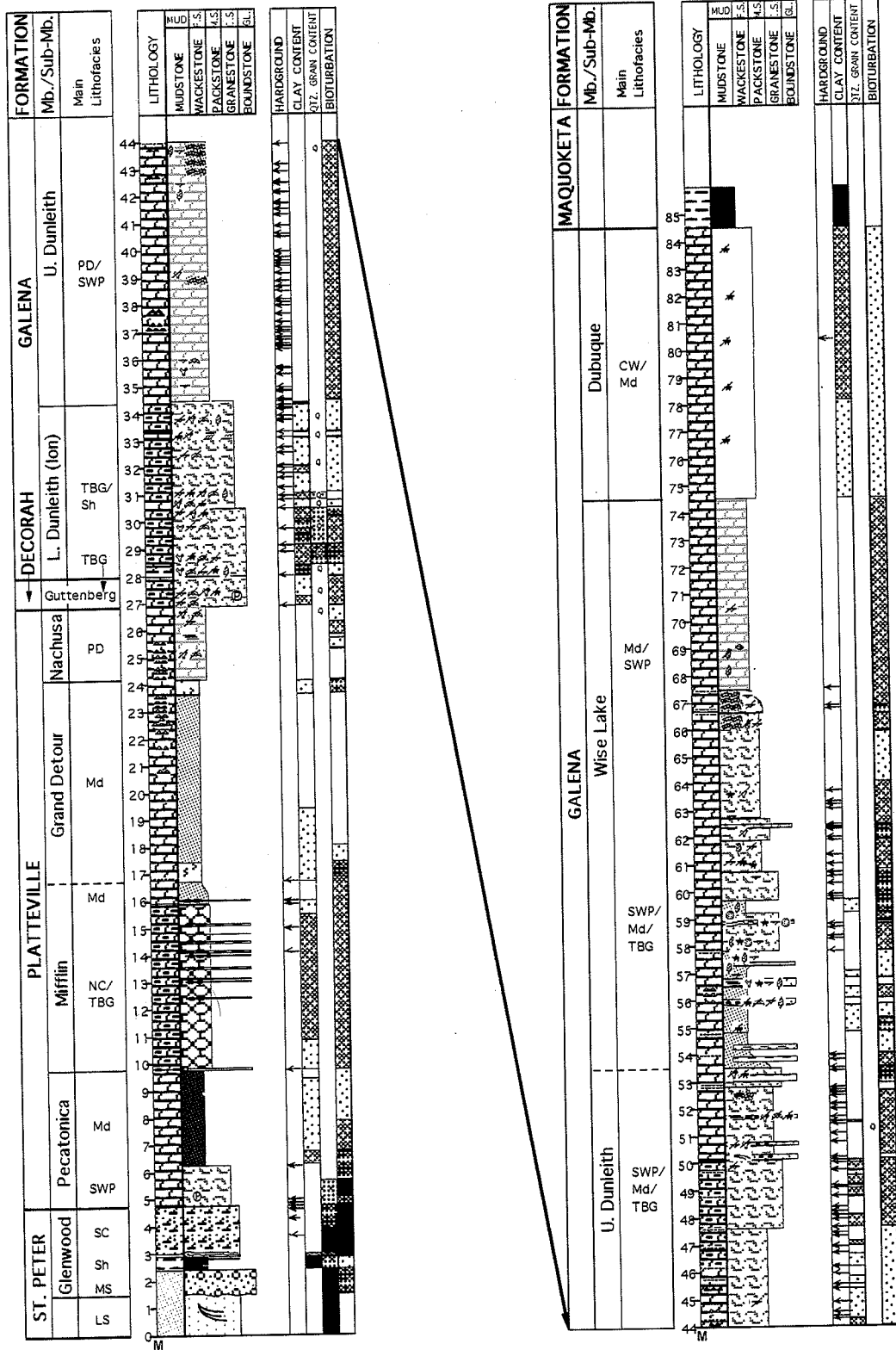


FIG. 7. Simplified composite section of the Sinnipee Group in E. WI. It does not reflect local variation in unit thickness and facies change. Key in Fig. 6 and in Appendix B, Fig. B-1, 2. See Table 2 for lithofacies code.

(Smith, 1991). The Prairie du Chien Group is overlain unconformably by the St. Peter Formation or by the sandy carbonate of the Glenwood Member without intervening sandstone (Fig. 8). Judging from the occurrence of abundant mud cracks and case-hardened intraformational conglomerates, the Prairie du Chien Group seems to have been deposited in a peritidal environment.

The St. Peter sandstone consists of fine- to medium-grained quartz-arenite, but the thickness is highly variable and thins out in many localities (Fig. 8). The quartz grains are well sorted and very well rounded. The St. Peter sandstone shows large-scale cross bedding and fine lamination. 1-2 cm-thick Fe-mineralized layers commonly bound the quartz-arenite. The Glenwood Member of the St. Peter Formation consists of bioturbated quartz-arenite, green shale, and sandy carbonate in ascending order (Fig. 9, Table 2). The Glenwood Member sandstone is distinguished from the sandstones of the St. Peter Formation mostly by the poor sorting, coarser grain size, and strong bioturbation. The Glenwood shale only occurs in southernmost study area and is highly fissile. The sandy carbonate contains medium- to coarse-grained quartz grains usually more than 50% in dolomite matrix/cements. The thickness of the Glenwood Member is variable, but a general southward thickening trend is observed (Fig. 6).

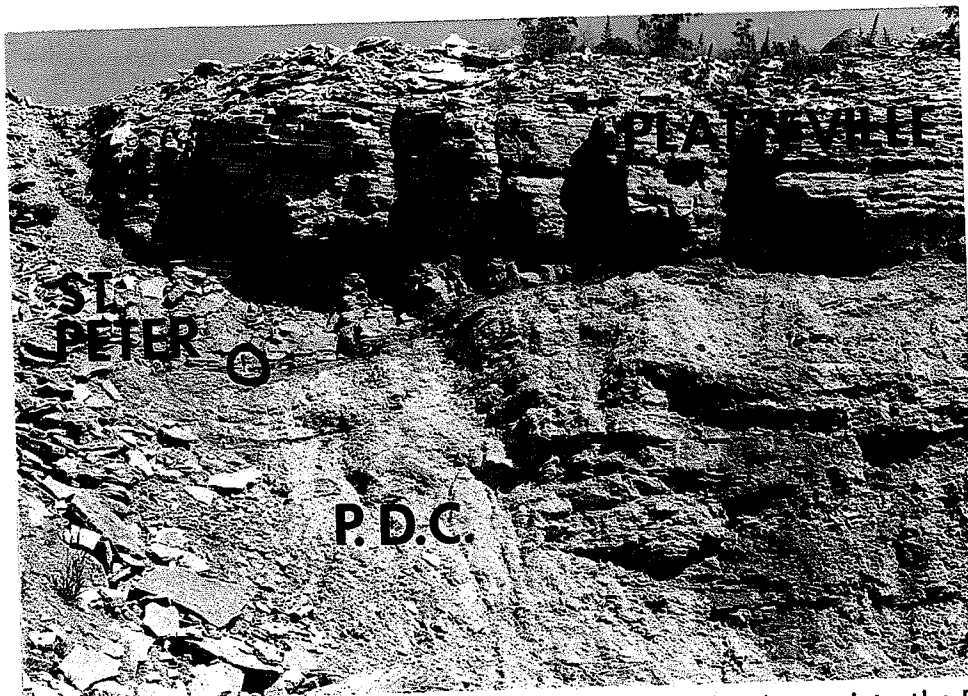


Fig. 8. Field photograph showing incision of the St. Peter sandstone into the Prairie du Chien Group. Hammer for scale at the unconformity surface (circle).

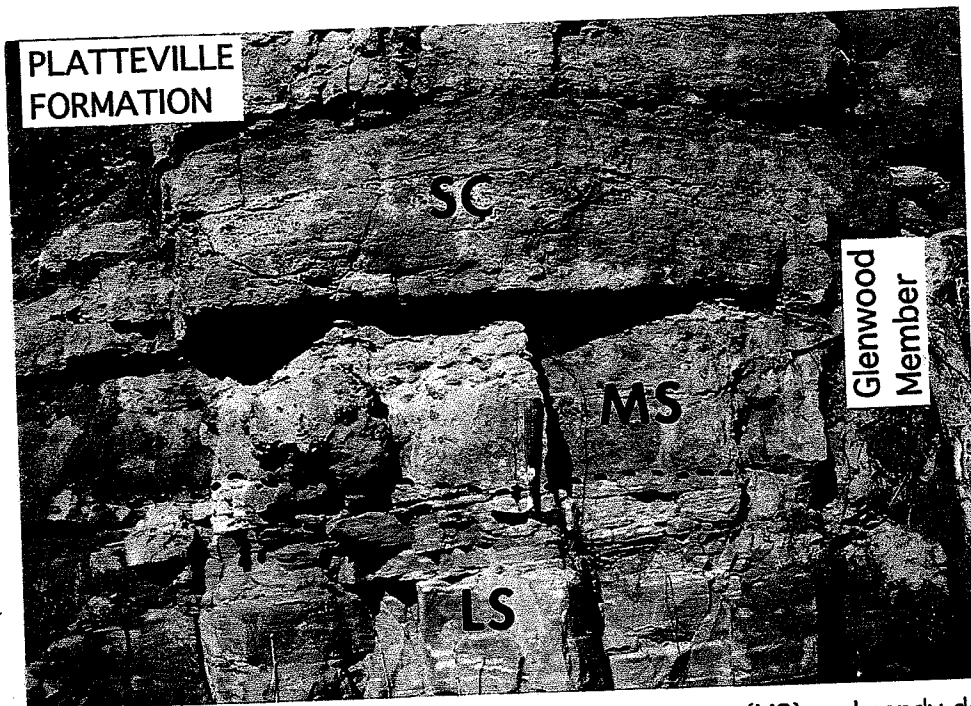


Fig. 9. Same outcrop as above showing massive sandstone (MS) and sandy dolostone (SC) of the Glenwood Member. Note the irregular boundary (dashed) between the laminated sandstone (LS) of the St. Peter Formation and the massive sandstone (MS) above.

2. PLATTEVILLE FORMATION

Previous Work

The Platteville Formation correlates to the Blackriveran Stage (Fig. 2) and is widely exposed over most of the midwest (Fig. 3) with remarkably consistent lithology over much of the area. Templeton and Willman (1963) and Willman and Kolata (1978) distinguished five formations in Illinois based on variations in argillaceousness, fauna, bed thickness, and lateral variation. The five formations are; Pecatonica, Mifflin, Grand Detour, Nachusa, and Quimbys Mill in ascending order (Fig. 10). The Pecatonica Formation consists of fine- to medium-crystalline, relatively argillaceous-free, medium-bedded, locally cherty dolomite that has a dense and finely vesicular texture and a mottled appearance (Willman and Kolata, 1978). The Mifflin Formation consists of thin-bedded shaly dolomite or limestone. The Grand Detour Formation consists of fine- to medium-crystalline, thin- to thick-bedded, light brown dolostone or gray limestone and clay. The Grand Detour clay is intermediate between the Mifflin Formation below and the massive and argillaceous-free Nachusa Formation above (Willman and Kolata, 1978). The Nachusa Formation consists of thick-bedded to massive carbonate or vuggy dolomite (Willman and Kolata, 1978). The Quimbys Mill Formation is largely medium to dark brown, lithographic limestone showing conchoidal fractures and light tan dolomite with smooth bedding surface in outcrop (Willman and Kolata, 1978; Ostrom, 1987a,b). Templeton and Willman's (1963) formations are considered as members and the Platteville Group as a formation in

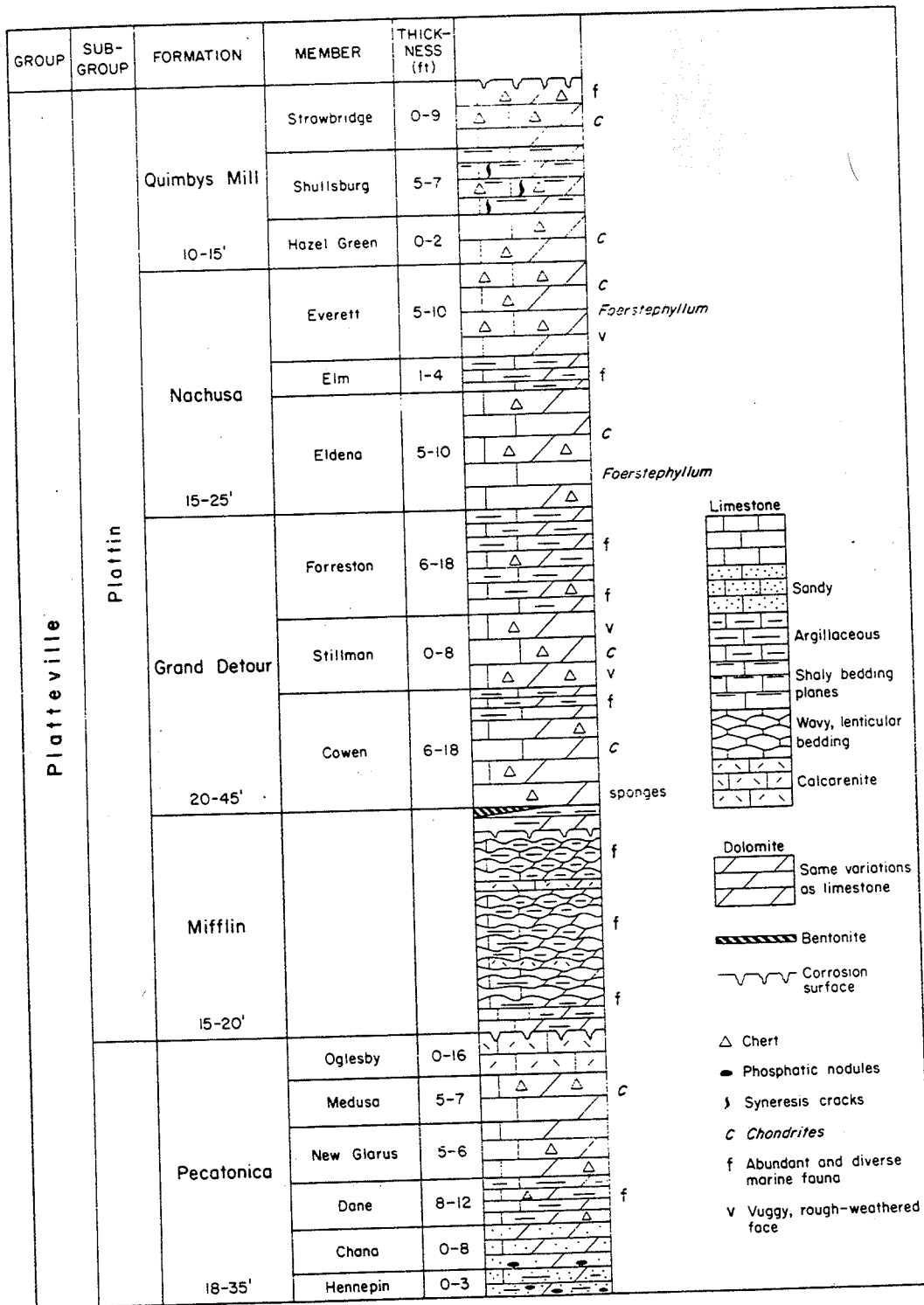


Fig. 10. General columnar section of the Platteville Group in northern Illinois (Willman and Kolata, 1978).

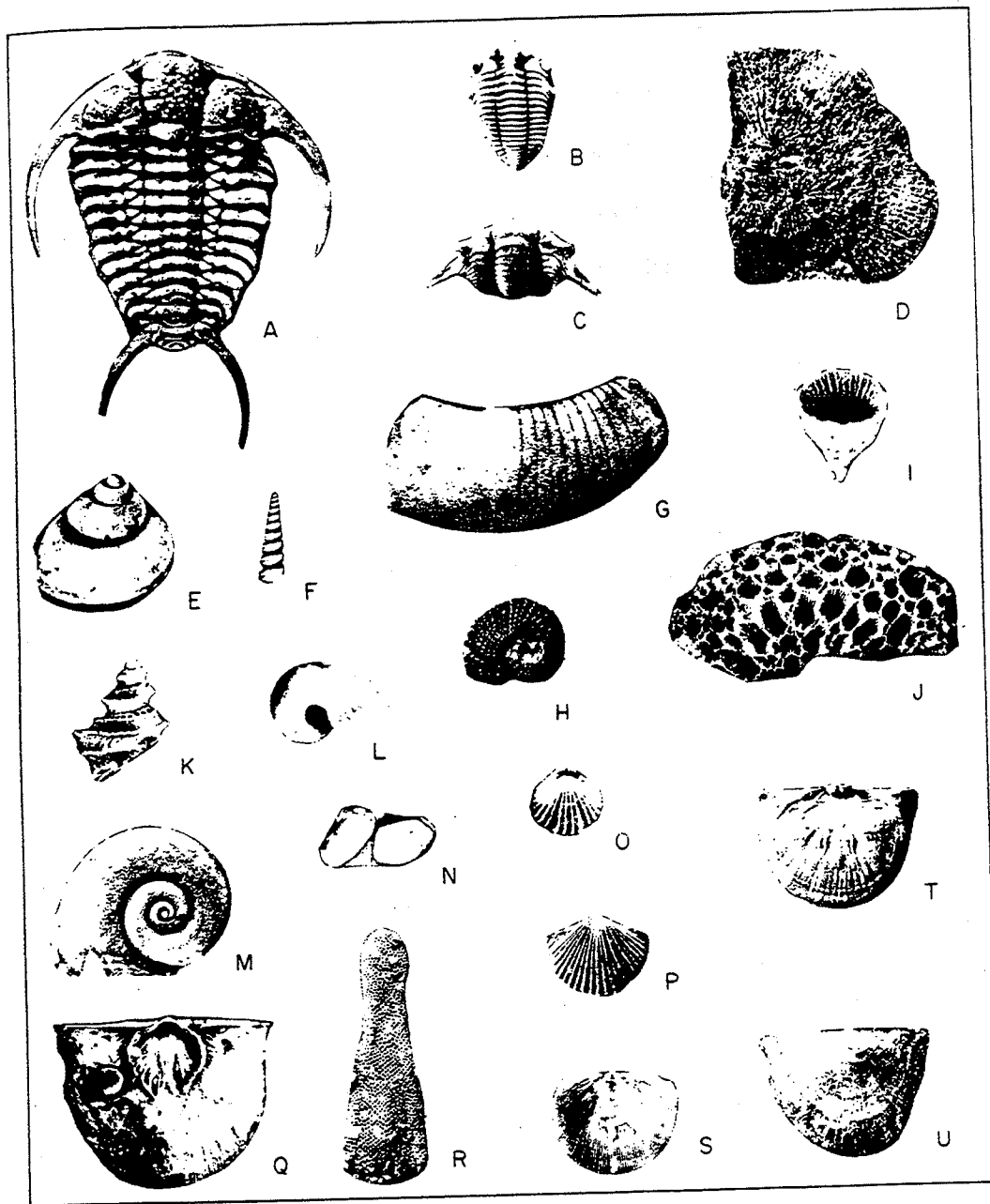


Fig. 11. Characteristic fossils of the Platteville Group in northern Illinois. A: *Ceraurus* sp., B: *Encrinurus* sp., C: *Thaleops ovata* Conrad, D: *Anthaspidella* sp., E: *Clathrospira* sp., F: *Ectomaria* sp., G: *Richardsondoceras* sp., H: *Phragmolites* sp., I: *Streptelasma* sp., J: *Foerstephyllum* sp., K: *Lophospira* sp., L: *Tetranota* sp., M: *Maclurites* sp., N: *Eoleperditia fabulites* (Conrad), O: brachial valve exterior of *Rostricellula minnesotensis* (Sardson), P: pedicle valve exterior of *Hesperorthis concava* Cooper, Q: pedicle valve interior of *Strophomena plattinensis* Fenton, R: *Leptotrypa hexagonalis* Ulrich encrusting *Hyolithes baconi* Shitfield, S: brachial valve exterior of *Campylorthis deflecta* (Conrad), T and U: brachial valve interior and pedicle valve exterior of *Öpikina minnesotensis* (N.H. Winchell). From Willman and Kolata (1978).

Wisconsin (Ostrom, 1967a). The Mifflin, Grand Detour, and Nachusa formations are grouped into one unit, the McGregor Member.

The Platteville Group in the northern Illinois contains diverse and abundant fauna that includes sponges, solitary and colonial corals, conularids, conodonts, graptolites, bryozoans, brachiopods, pelecypods, gastropods, cephalopods, trilobites, ostracods, and echinoderms (Willman and Kolata, 1978; Fig. 11). Among them, the brachiopods and bryozoans are most abundant. The relative abundance of some species is useful in stratigraphic units.

Although lithologic descriptions and correlative work for the Platteville strata are many in the upper Mississippi valley area (Agnew et al., 1946, 1956; Templeton and Willman, 1963; Ostrom, 1969; Willman and Kolata, 1978; Ostrom, 1987a,b), sedimentological studies including depositional environment interpretation and facies analysis are scarce except few (Byers, 1983; Mossler, 1985). The strata equivalent to the Platteville Formation are widely studied in New York (Walker, 1973), Ohio (Stith, 1979), and Indiana (Droste and Shaver, 1983; Wilcer, 1989), and they are interpreted as deposited in peritidal (Walker, 1973; Stith, 1979; Droste and Shaver, 1983) and shallow subtidal (Wilcer, 1989) settings.

Lithostratigraphic Description

Figure 12 shows the correlation of the lithostratigraphic units described in eastern Wisconsin with those of Upper Mississippi Valley. Notice the absence of the upper Pecatonica and Nachusa, and Quimbys Mill members in eastern Wisconsin. The Platteville Formation in

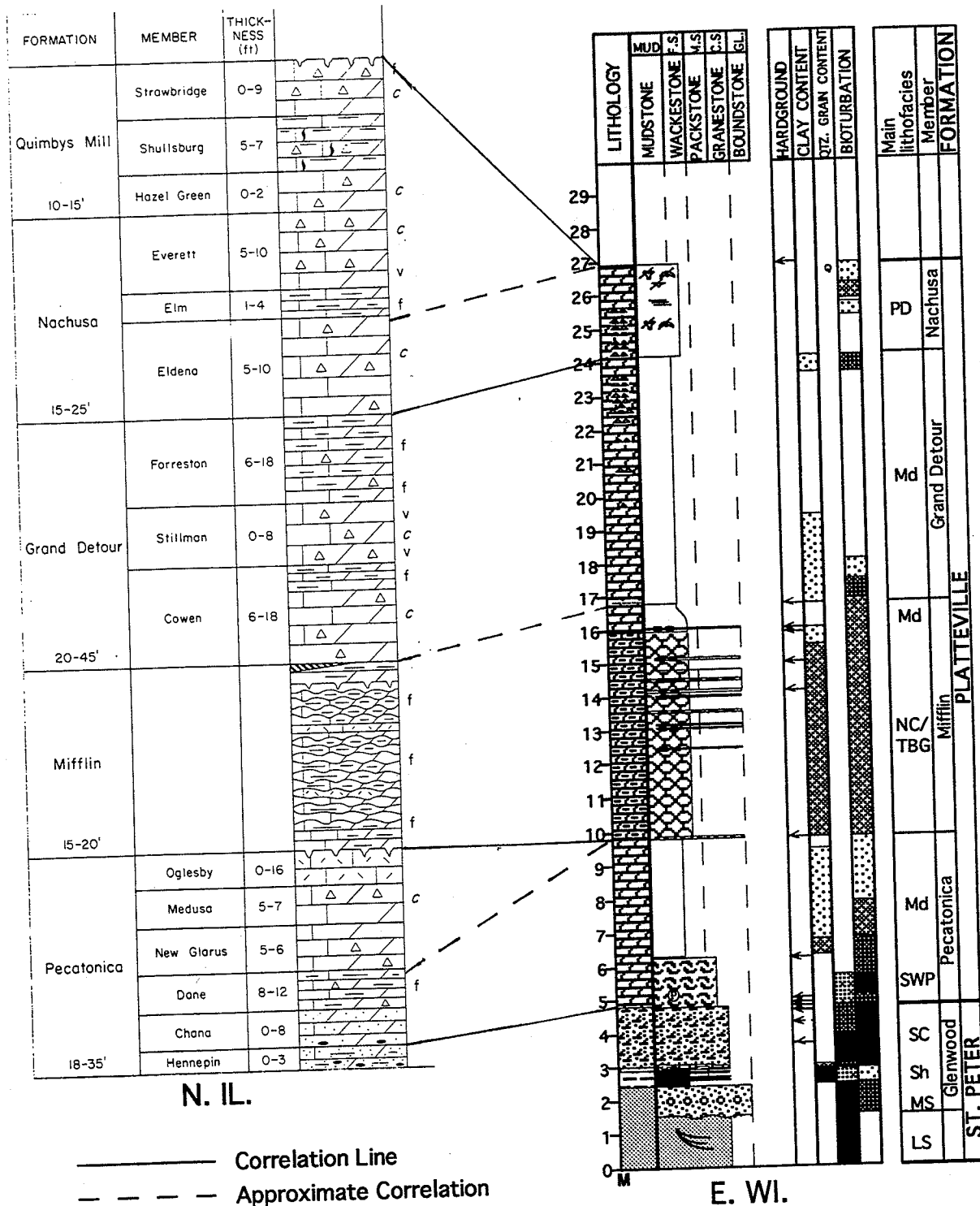


Fig. 12. Correlation of the Platteville Formation from eastern Wisconsin to the stratigraphic standard in the U. Mississippi Valley. Key for the standard column is in Fig. 10, and for the right column is in Figs. B-1, 2. See text for stratigraphic standard. Notice the thickness changes, and the absence of the upper Pecatonica Formation, upper Nachusa and Quimbys Mill formations in eastern Wisconsin.

eastern Wisconsin is subdivided into four lithostratigraphic units (Table 3; Fig. 12). The lowermost unit, Pecatonica Member, consists of fine- to medium-crystalline dolostone, is gray to purplish brown in color in fresh surfaces. Its thickness ranges 3-8 m and gradually decreases to the north. The lower boundary of the Pecatonica Member is usually sharp to gradational and is marked by ferruginous hardgrounds. The upper boundary of the Pecatonica Member is very sharp with a prominent hardground that can be traced throughout the study area. The hardground is stained by pyrite (Fig. 13) and its surface is riddled with 1-2 mm-wide borings. The Pecatonica Member is characterized by relatively argillaceous-free carbonate lithology compared to the overlying units. According to the difference in argillaceousness and crystal size, the Pecatonica Member is subdivided into two sub-members. The lower sub-member has bioclastic wackestone to packstone texture (Fig. 34), and contains small amount of floating quartz and phosphate grains at the base. It has several ferruginous hardgrounds, which are more abundant at the base. The lower sub-member corresponds to the Chana Member following the Illinois nomenclature (Willman and Kolata, 1978). In order of abundance, the bioclasts consists of skeletal fragments of crinoids, brachiopods, and trilobites. Also observed are cephalopod molds (Fig. 14). The thickness of the Chana sub-member ranges 1.2-2.0 m. A significant hiatus is inferred below this sub-member by the prominent ferruginous hardground surface on top of Glenwood Member below. The upper sub-member is medium gray to purplish gray in color, and is slightly to moderately argillaceous with 0.5-1.5 cm-thick argillaceous partings

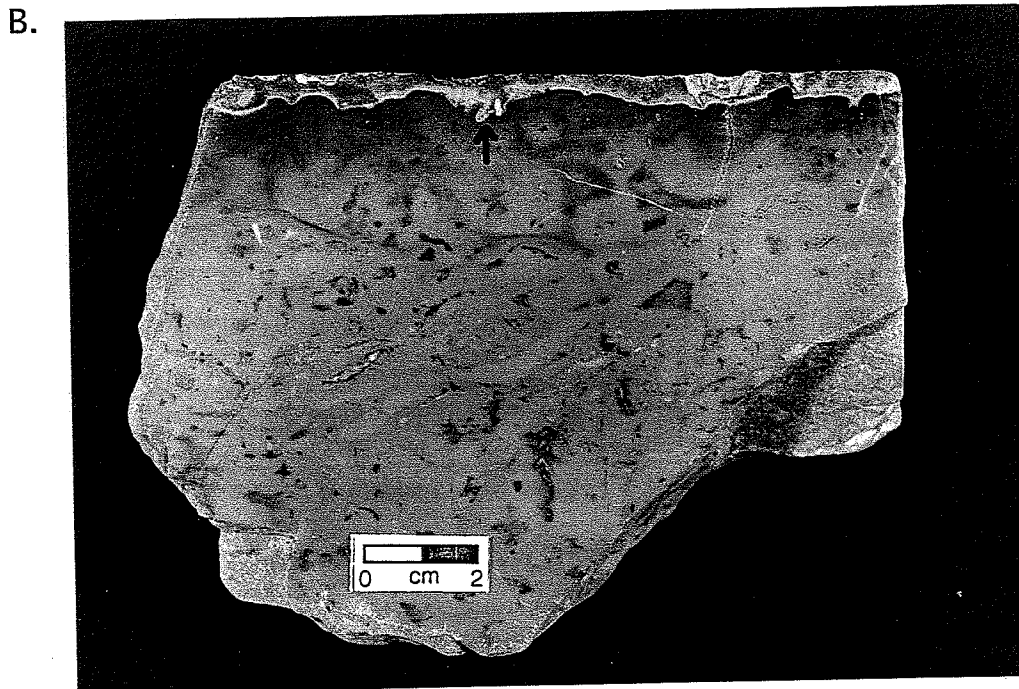
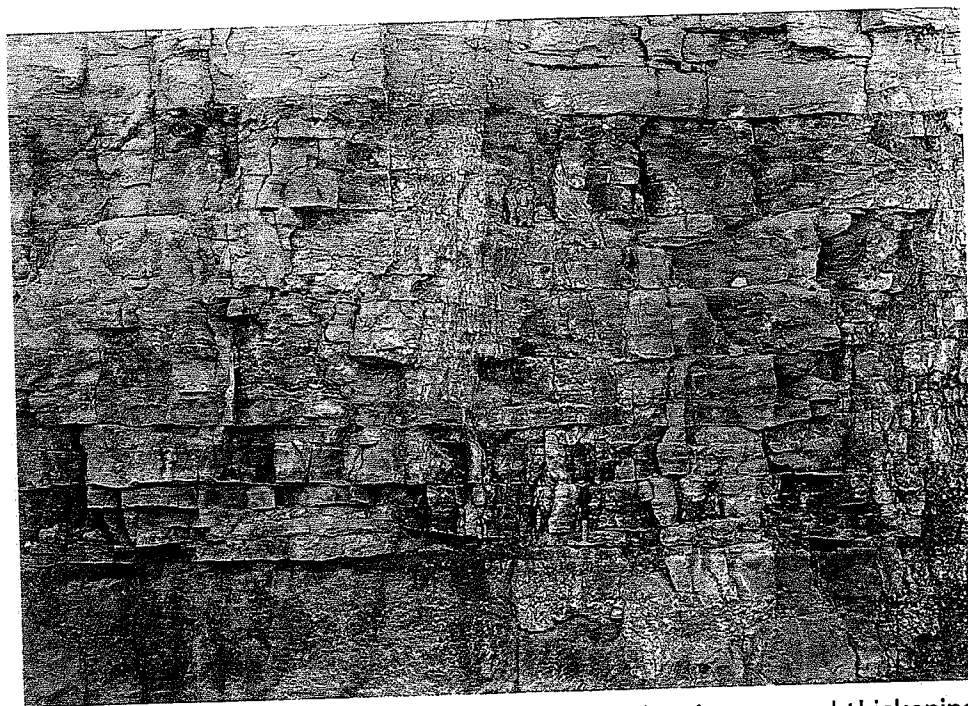


Fig. 13. Hardground on top of the Pecatonica Member. A: Field photograph of the mottled mudstone of the Dane sub-member overlain by the nodular carbonate of the Mifflin Member. Pencil for scale is 14 cm long. Sun Prairie Qr. Locality 17. B: Rock slab taken from the top of the Dane sub-member, the same outcrop as A, showing two closely spaced hardgrounds stained by dark gray pyrite. Note the 2 mm-wide borings at the hardground surfaces (arrows) [U.W.1896/1].



Fig. 14. Field photograph of the Chana sub-member showing a cephalopod mold. Coin for scale is 2.5 cm long. Sun Prairie Qr., Locality 17.



DANE

CHANA

Fig. 15. Field photograph of the Dane sub-member showing upward thickening in bed thickness. Note the wavy bedding planes truncating underlying beds in the lower part of the Dane sub-member. Hammer for scale at the boundary with the underlying Chana sub-member. Sun Prairie Qr., Locality 17.

(Fig. 15). It is very fine-crystalline and mudstone-textured. The upper sub-member corresponds to the Dane Member following the Illinois nomenclature (Willman and Kolata, 1978). It is weakly to moderately bioturbated by 0.5 cm-wide dark gray mottled burrows. Fauna in this sub-member includes brachiopods, crinoids, pelecypods, and gastropods. The thickness of the Dane sub-member ranges from 1.2 m to 6.5 m, gradually increasing to the south (Fig. 6). The lower portion of the Dane sub-member shows wavy bedding plains truncating underlying beds (Fig. 15). The boundary between the Chana and Dane sub-members is sharp in north (north of Waukesha County) whereas gradational in south (Racine and Kenosha counties) (Fig. 6).

The middle unit, the Mifflin Member, is very fine- to fine-crystalline dolostone or dolomitic limestone. It is very thin-bedded and is the most argillaceous unit of the Platteville Formation (Fig. 16). It consists of fossiliferous argillaceous mudstone to wackestone with abundant thin-bedded intraclastic/bioclastic grainstone beds. It is greenish to bluish gray in color. Its thickness gradually decrease to the north, ranging from 9.2 m in Kenosha County to 0.3 m at Ripon in Fond du Lac County (Fig. 6). It is generally moderately to strongly bioturbated by 0.5 cm-wide *Chondrites* burrows. Fauna in this unit includes brachiopods, gastropods, crinoids, and rugose corals. In general, the upper part of this unit shows gradual upward decrease in clay content becoming carbonate at the top while the lower part shows gradual increase in clay content particularly in the south (Racine and Kenosha counties). Prominent ferruginous hardgrounds bound the Mifflin Member above and below.

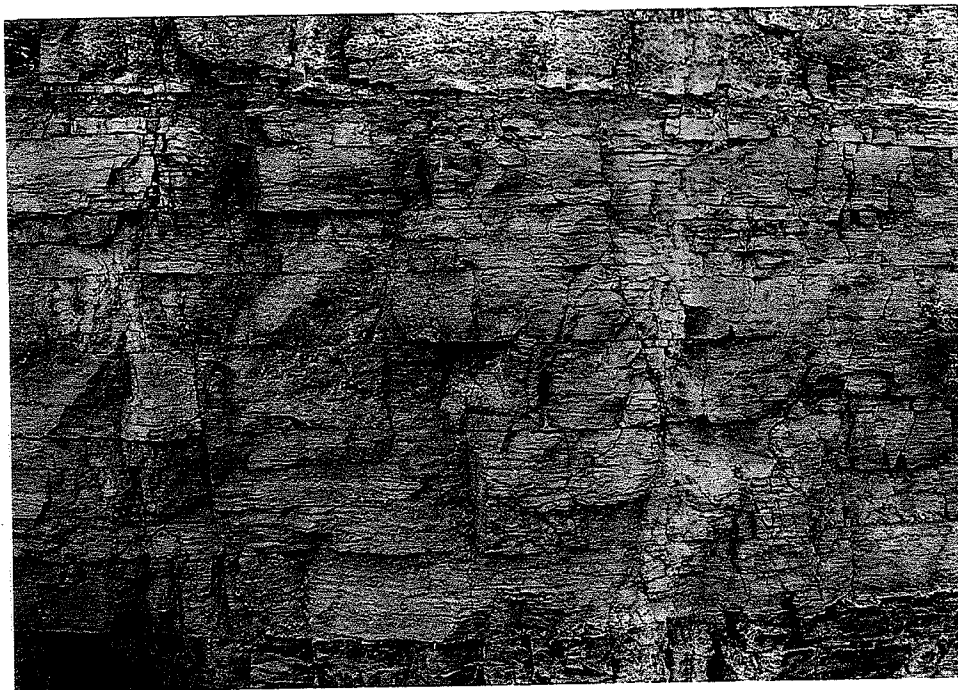


Fig. 16. Field photograph of the Mifflin Member showing greenish-gray color due to high content of green clay. Hammer for scale. Sun Prairie Qr., Locality 17.

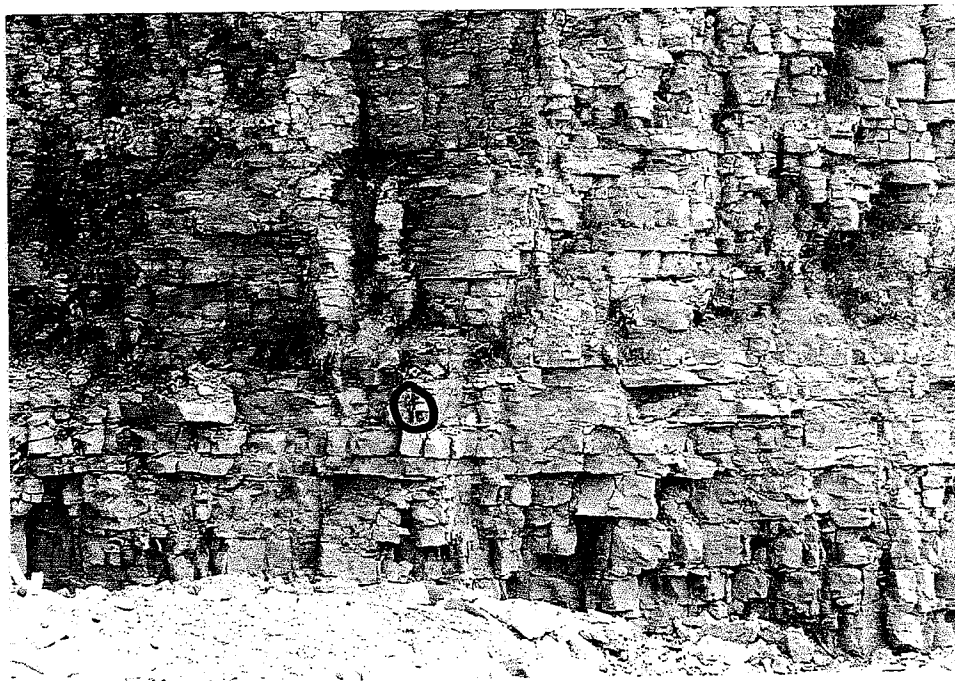


Fig. 17. Field photograph of the Grand Detour Member showing light purplish brown color. Hammer for scale in the circle. Watertown Qr., Locality 2.

The Grand Detour Member is about 7.5-8 m thick. It is thin- to medium-bedded, very fine-crystalline dolostone (Fig. 17) locally containing abundant white chert nodules. This unit is mostly mudstone-textured with occasional very thin grainstone lenses less than 2 cm thick. This unit is less fossiliferous than the other units. The fauna includes brachiopods, gastropods, bryozoans, and crinoids. In the southeastern study area (Racine and Kenosha counties), this unit is slightly coarser crystalline and more vesicular, and contains more thin grainstone beds. Its color is mostly light purplish-brown on top and gray in the basal and upper middle parts. The gray-colored interval is characterized by strong bioturbation and slightly more argillaceous than the purplish brown colored interval that is relatively free of argillaceous material.

The thickness of the uppermost unit, Nachusa Member, is variable (3.3-4.4 m thick), but a gradual northward thinning trend is observed. It is characterized by relatively argillaceous-free lithology and vesicular to vuggy porosities (Fig. 18). The porosities generally increase upward. Its color is buff brown to light tan. Bryozoan molds and moldic porosity are common in upper part of this unit and they are partly or completely filled with fine-crystalline dolomite crystals which are inferred to have been originally lime mud. Other fauna in this unit is crinoids, brachiopods, and trilobites. This unit contains a few very thin fine-grained grainstone beds showing lamination, and is coarser crystalline and more fossiliferous. White chert nodules are abundant in this unit. A prominent ferruginous hardground is observed on top of the Nachusa Member in all the outcrops and cores. The burrows associated with the

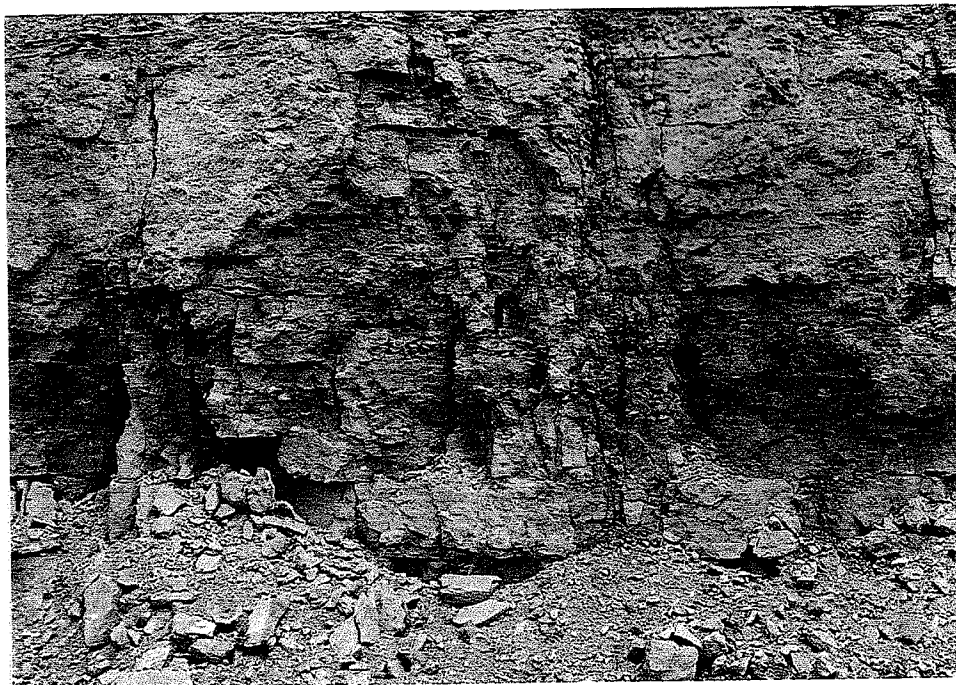


Fig. 18. Field photograph of the Nachusa Member showing rough-weathered surface due to high porosity. Hammer for scale. Fort Atkinson Qr., Locality 1.

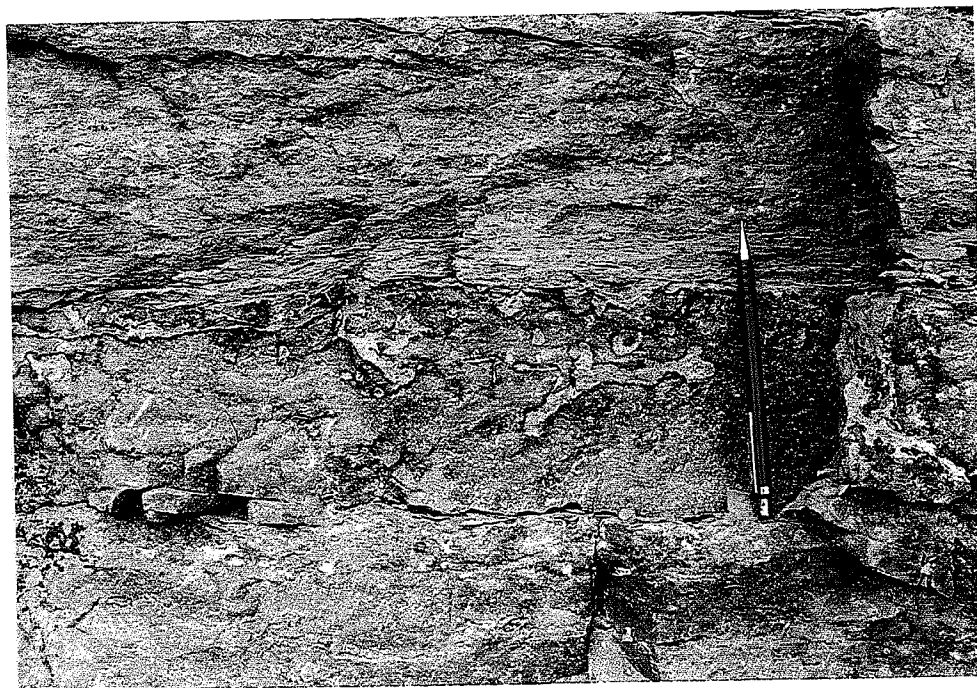
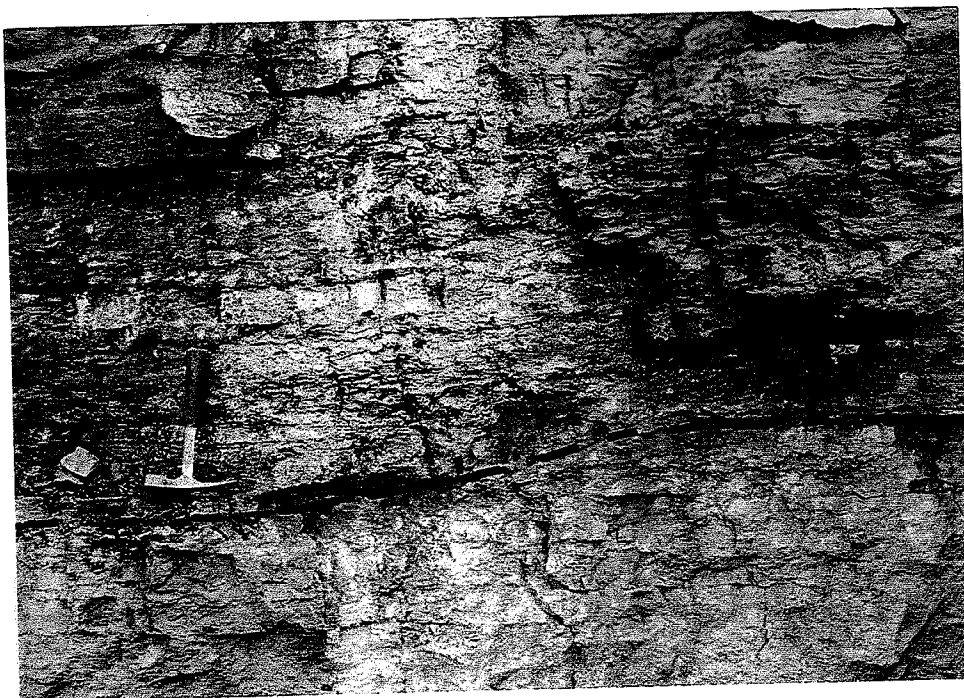


Fig. 19. Hardground surface separating the Platteville Formation from the Galena Formation. *Thalassinoides* burrows are filled with argillaceous material from the overlying unit above. Note the dark gray pyrite staining on the hardground surface and the burrow walls. Pencil for scale is 14 cm long. Duck Creek Qr., Green Bay, Brown County.

A.



B.

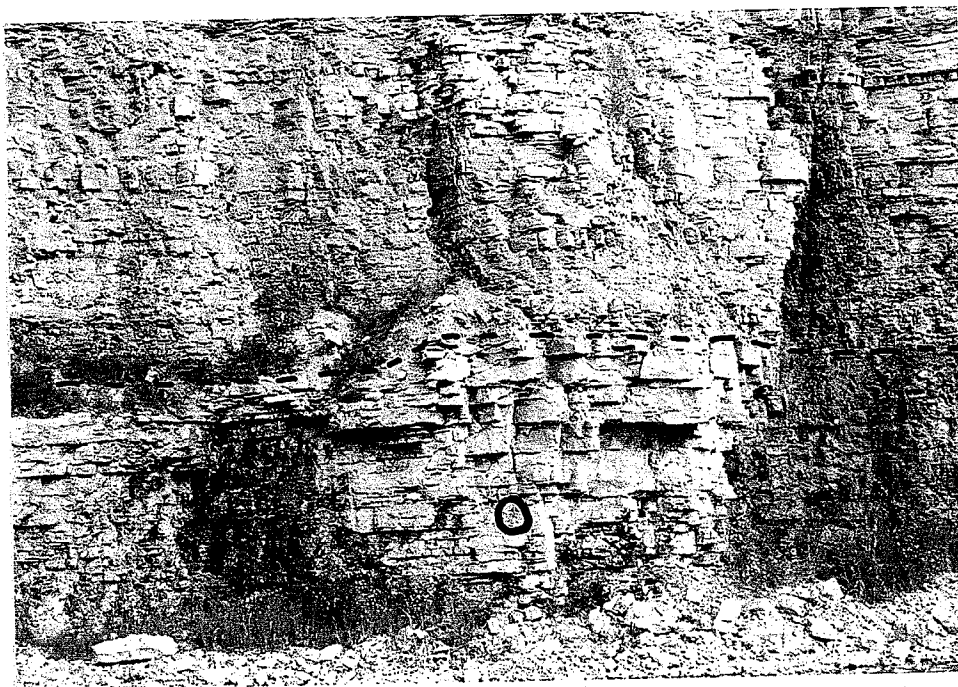


Fig. 20. Unconformity surface on top of the Platteville Formation overlain by the Guttenberg Member of the Decorah Formation (A) or the Dunleith Member of the Galena Formation (B). A: Slightly undulating unconformity surface (dashed). Note the termination of bedding planes below and above the unconformity. Fort Atkinson Qr., Locality 1. B: Watertown Qr., Locality 2. Note the termination of the bedding planes of the Platteville Formation below the unconformity surface (dashed). Hammer for scale in the circle.

hardgrounds are sometimes filled with green shale from the overlying unit (Fig. 19). In few locations, the upper boundary is a subtle low angle truncation surface disconformably overlain by the Decorah or Galena Formation (Fig. 20).

3. DECORAH AND GALENA FORMATIONS

Previous Work

The Decorah and Galena formations correlates to the Rocklandian to the middle of Edenian stages (Fig. 2). The Decorah and the Galena formations are sometimes referred as the Trentonian Stage which corresponds to the Rocklandian to Shermanian Stages. The Decorah and Galena formations are grouped into the Galena Group in the upper Mississippi Valley area. Templeton and Willman (1963) described in Illinois five formations in the Galena group: Spechts Ferry and Guttenberg formations included in the Decorah subgroup, and Dunleith, Wise Lake, Dubuque formations included in the Kimmswick subgroup (Fig. 21). The Spechts Ferry Formation is dominantly a shale lithology containing thin beds of lithographic limestone and bentonites (Willman and Kolata, 1978). The Guttenberg Formation is a very fine-grained to lithographic, light pinkish tan limestone or brown vesicular dolostone. It is characterized by thin reddish brown shale partings (Willman and Kolata, 1978). The Dunleith Formation is mostly slightly argillaceous, cherty dolostone (Willman and Kolata, 1978). The lower two members of the Dunleith Formation, Buckhorn and St. James, are very argillaceous and the argillaceousness increase toward source areas on

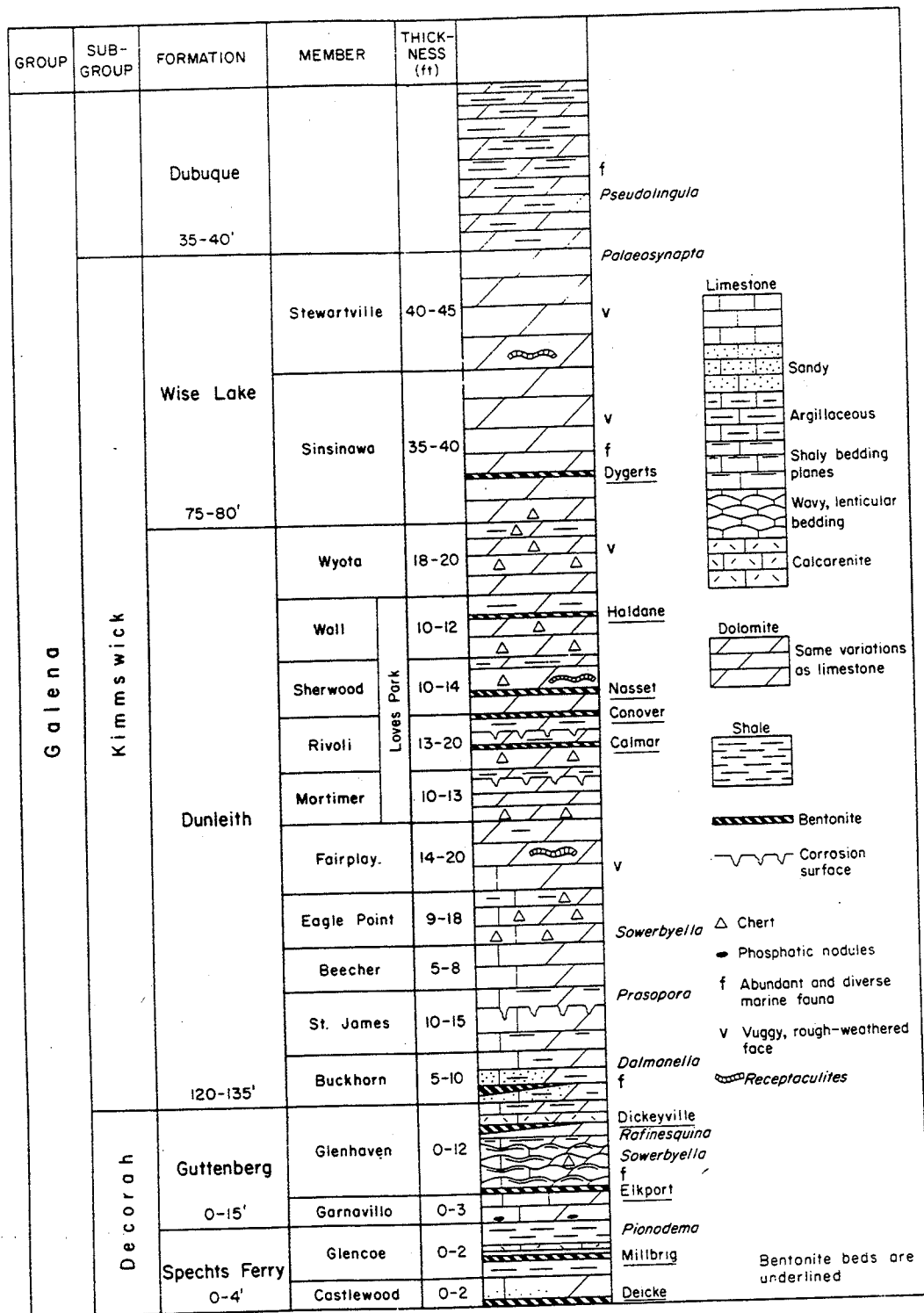


Fig. 21. General columnar section of the Galena Group in northern Illinois (Willman and Kolata, 1978).

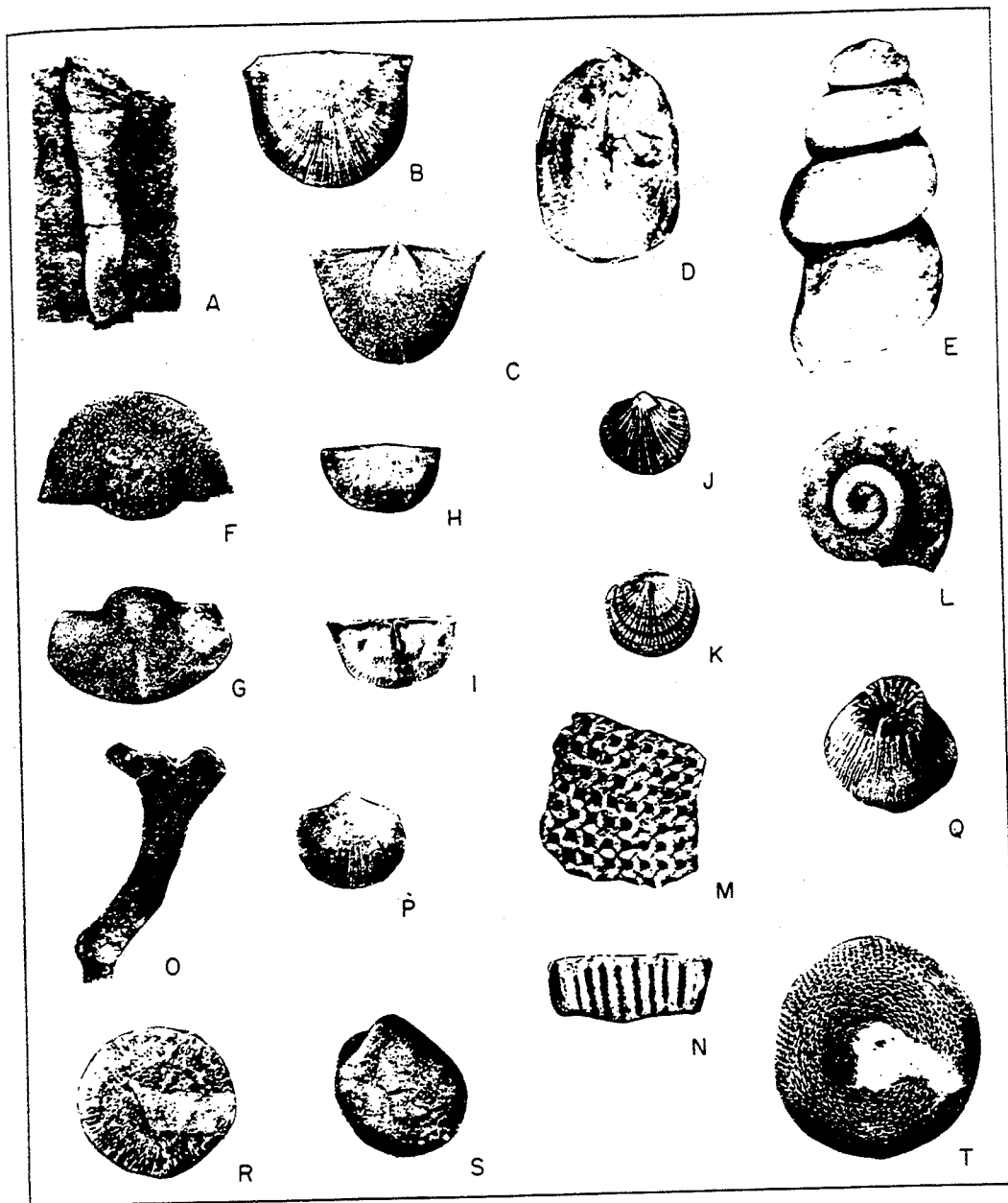


Fig. 22. Characteristic fossils of the Galena Group in northern Illinois. A: *Palaeosynapta flaccida* Weiss, B: pedicle valve exterior of *Rafinesquina trentonensis* (Conrad), C: interior mold of pedicle valve of *Rafinesquina* sp., D: *Pseudolingula iowensis* (Owen), E: *Hormotoma major* (Hall), F and G: cephalon and pygidium of *Illaenus* sp., H and I: pedicle valve exterior and brachial valve interior of *Sowerbyella punctostriata* (Mather.), J and K: pedicle and brachial exterior of *Dalmanella* sp., L: *Liospira* sp., M and N: top and side views of *Receptaculites oweni* Hall, O: trepostome bryozoan, P: pedicle valve exterior of *Pionodema subaequata* (Conrad), Q: *Streptelasma* sp., R: basal view of *Prospora* sp., S: *Vanuxemia* sp., T: *Ischadites iowensis* (Owen). From Willman and Kolata (1978).

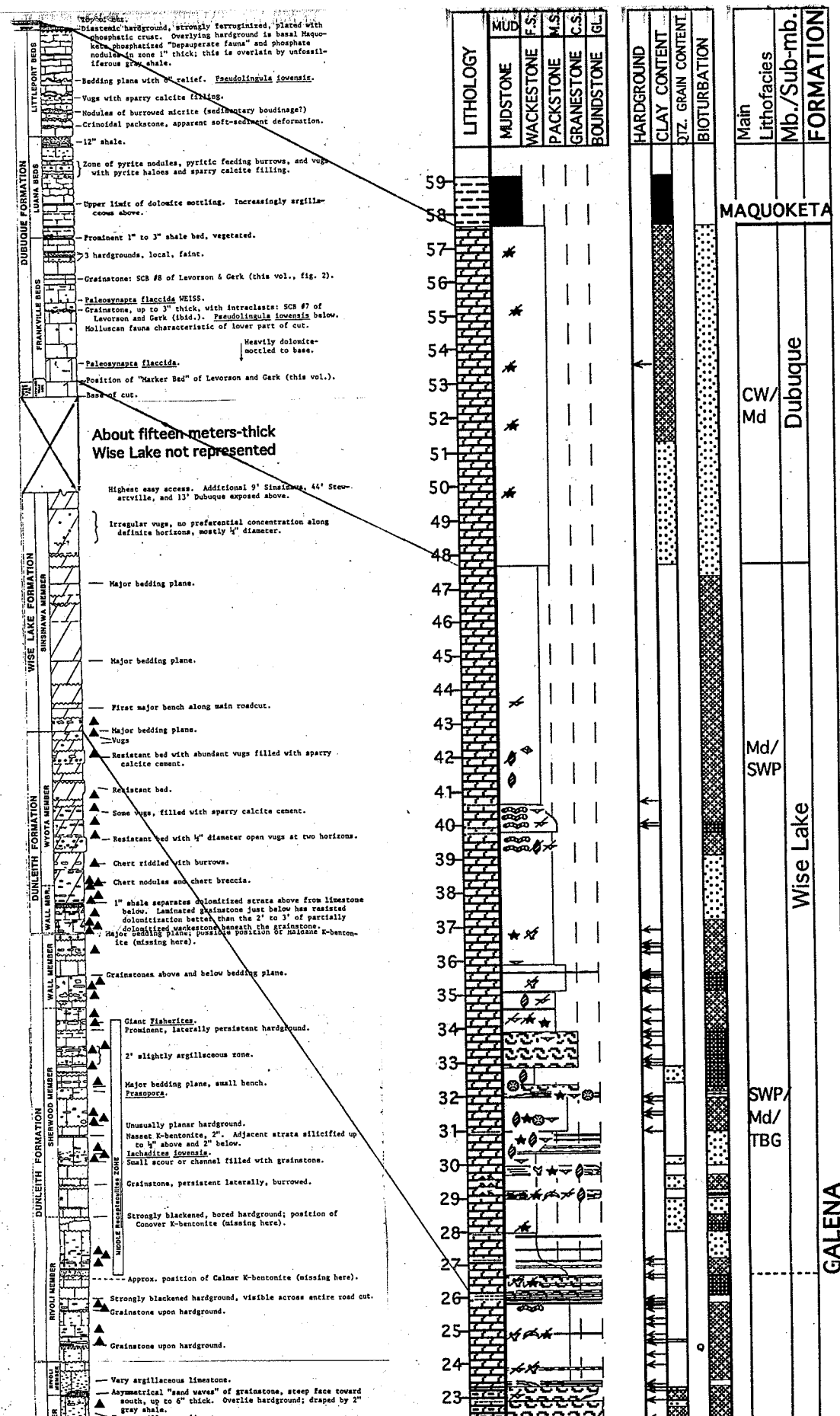
the Transcontinental Arch, thus they are named Ion Member of the Decorah Formation in Iowa (Witzke, 1980). The Wise Lake Member Formation overlies the Dunleith Formation, and is argillaceous-free, vesicular to vuggy carbonate. It is distinguished from the underlying Dunleith Formation by the generally non-cherty, argillaceous-free lithology (Willman and Kolata, 1978). The uppermost unit, the Dubuque Formation is characterized by light brown shaly partings and the argillaceousness increases upward (Willman and Kolata, 1978). In Wisconsin, these formations are classified as members. Four members are identified in this study: the Guttenberg Member (Decorah Formation), and the Dunleith, Wise Lake, and Dubuque members (Galena Formation) (Table 3).

Figure 22 shows the typical biota in the Galena Group in northern Illinois. The relative abundance of some species is useful in stratigraphic units (Willman and Kolata, 1978). Among them, the *Receptaculites* shows widespread 'blooms' in specific stratigraphic intervals, which is probably related to environmental changes.

Sedimentological studies for the Galena and equivalent strata in the upper Mississippi area have been done by Delgado (1983a) and Bakush (1985). Open marine shallow ramp setting is suggested in their study for the depositional environment of the Galena Formation.

Lithostratigraphic Description

Figure 23 shows the correlation of the lithostratigraphic units described in eastern Wisconsin with those in Upper Mississippi Valley.



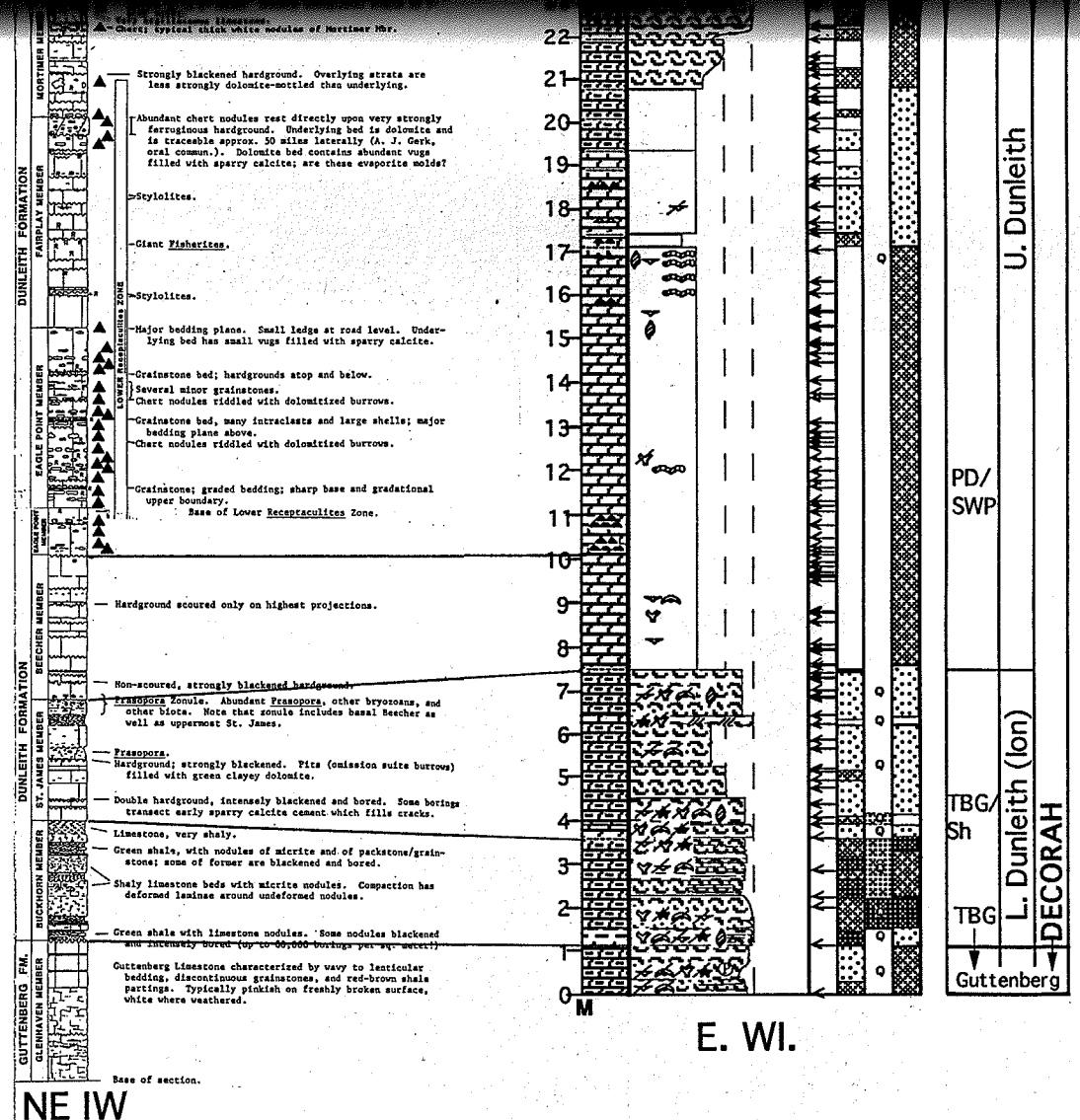


Fig. 23. Correlation of the Galena Formation from eastern Wisconsin to the stratigraphic standard in the U. Mississippi Valley. Key for the composite section in the right in Figs. B-1, 2. The standard section in the left is modified from Delgado (1983b). Key for the standard section is in Appendix D.

Decorah Formation

The Decorah Formation in eastern Wisconsin unconformably overlies the Platteville Formation (Fig. 20A), and correlates to the Guttenberg lithostratigraphic unit of Willman and Kolata (1988). Its thickness reaches up to 1.1 m, decreasing to the north to completely pinch out north of Jefferson County (Fig. 5; Appendix C). It is thin- to medium-bedded with reddish brown to green shaly partings. It is highly fossiliferous, and is composed mostly of many amalgamated thin-bedded skeletal grainstone beds. The fauna in this unit is brachiopods, bryozoans, crinoids, trilobites, and probable ostracods. It is slightly to moderately argillaceous and the argillaceousness gradually decrease to the south. Silt-sized phosphate grains are concentrated abundantly in the shaly partings, which results in the characteristic reddish brown color (Figs. 24, 25). A very prominent hardground separates this formation from the overlying Galena Formation (Fig. 24).

Galena Formation

The Galena Formation in eastern Wisconsin conformably overlies the Decorah Formation or unconformably overlies the Platteville Formation with a very sharp boundary. Three members are distinguished (Table 3; Fig. 23). The lowermost unit, Dunleith Member is subdivided into two sub-members; the lower and upper Dunleith sub-members. The lower Dunleith sub-member correlates to the Ion Member of the Decorah Formation in Iowa (Agnew et al., 1956), and is named Ion sub-member in this study. The Ion sub-member is characterized by high content of fine grained siliciclastics and appears shaly when



Fig. 24. Rock slab photograph showing two amalgamated grainstone beds. Note the reddish-brown color and the prominent Fe-rich hardground surface on top of the unit Guttenberg Member. Sample taken from the top of the Decorah Formation at Fort Atkinson Qr., Locality 1 [U.W.1896/2].

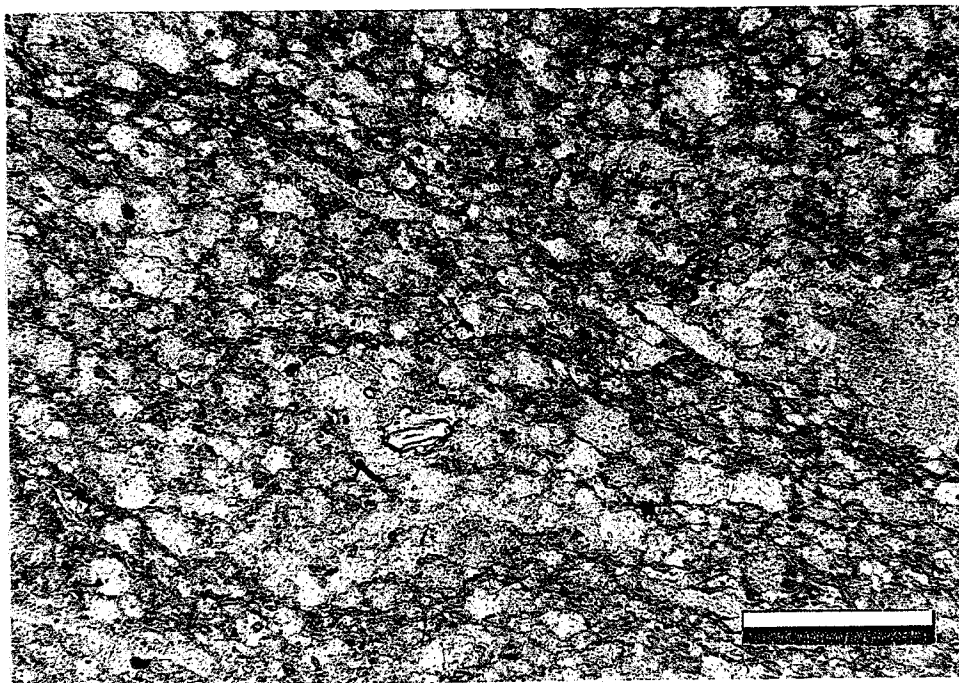


Fig. 25. Photomicrograph of a grainstone sample taken from the Guttenberg Member at Fort Atkinson Qr., Locality 1. Note the silt size phosphate grains. PPL (plane-polarized light). Scale bar is 0.5 mm long [U.W.1896/16].

weathered (Fig. 26). It is highly fossiliferous and contains open marine fauna such as brachiopods, bryozoans, crinoids, trilobites, and gastropods in order of abundance. The siliciclastics consist mainly of detrital clay and minor subrounded to subangular silt-sized grains of quartz and minor feldspar. The clay content generally decreases upward and southward where this unit becomes carbonate in southernmost Wisconsin (Appendix C). This unit is thin- to medium-bedded, medium-crystalline dolostone intercalated with cm-thick green shale partings. The dolostone beds are mostly bioclastic packstone to grainstones. Most of the packstone beds are moderately to very argillaceous and highly bioturbated by burrows filled with green shale. Some of the grainstone beds show parallel lamination or high-angle cross bedding. The shaly nature of the packstone beds is thought to be due to the pervasive bioturbation, and most of them might have been grainstone beds originally. Hardgrounds are abundant in this unit particularly in less argillaceous carbonate. Based on the clay content, the Ion sub-member is subdivided into a lower argillaceous sub-unit that correlates to the Buckhorn Member, and an upper less argillaceous sub-unit that correlates to the St. James Member (Fig. 26; Templeton and Willman, 1963). Both sub-units become less argillaceous to the south.

The upper Dunleith is medium-crystalline dolostone locally with chert nodules. It is medium- to thick-bedded with mm-thick, thin shale partings. The clay content is much lower than the unit below and it gradually decreases upward. Terrigenous silt is less than 1% in general. Although the upper Dunleith is relatively argillaceous-free to the south, it becomes moderately to very argillaceous to the north in

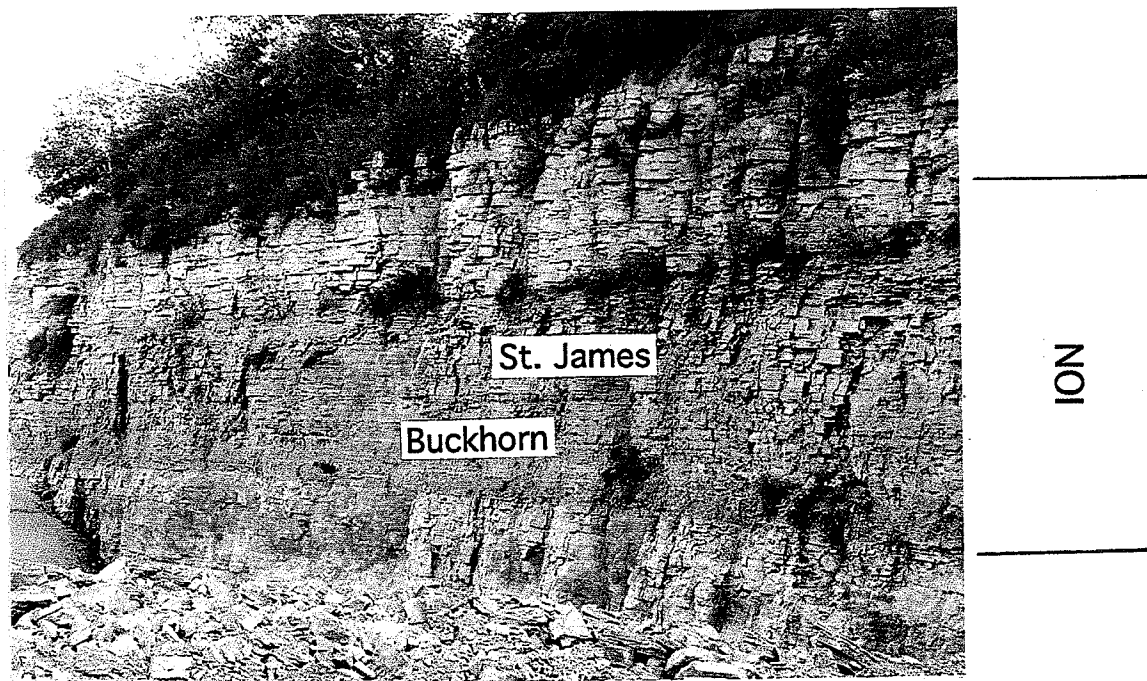


Fig. 26. Field photograph of the Ion sub-member showing gray color due to high clay content. The thickness of the Ion sub-member is 6.5 m. Note the lighter color of the upper sub-unit due to less clay content. Watertown Qr., Locality 2.

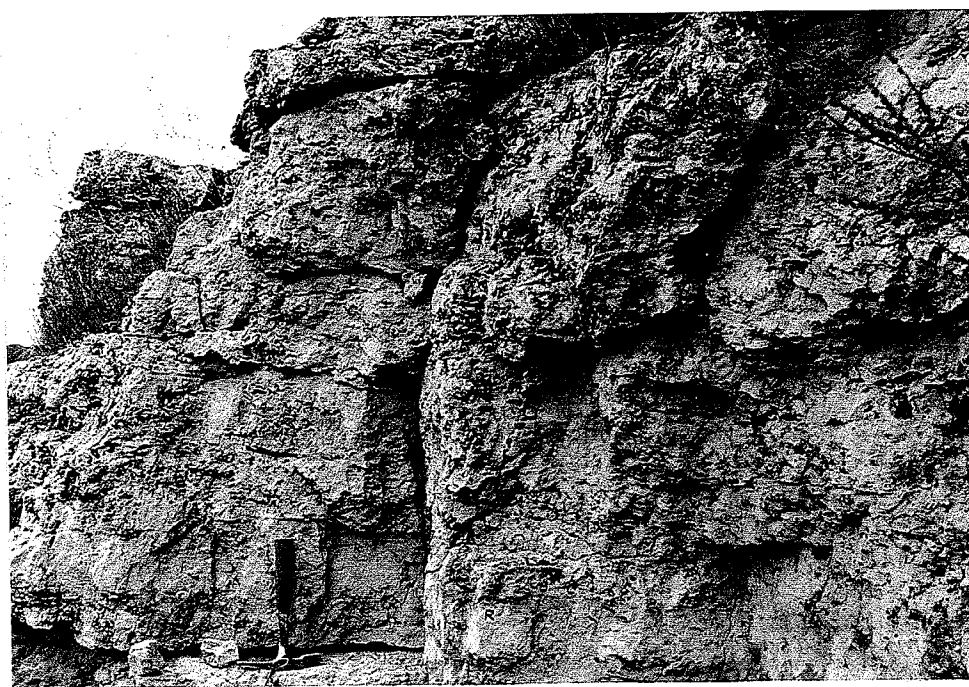


Fig. 27. Field photograph of the upper Dunleith sub-member showing relatively argillaceous-free lithology. Note the rough-weathered surface due to vesicular and vuggy porosity. Hammer for scale. Fort Atkinson Qr., Locality 1. The letter 'R' on the outcrop represents receptaculites occurrence.

Winnebago to Brown counties (Freiberg, personal communication). In general, the vertical change in lithology is very subtle in south where the Galena Formation lacks in argillaceous material and dolomitization is more intense, whereas it is rather well recognized in north. The textures are difficult to identify, but general wackestone to packstone textures are observed in rock slabs. It is moderately bioturbated mainly with 1-2 cm-wide *Thalassinoides* burrows. Vesicular porosity is common throughout, with minor moldic to vuggy porosity. In general, burrow-fills are coarser crystalline and this leads to higher vesicular porosity, which with the vuggy porosity results in rough weathered surface on outcrop (Fig. 27). Common biota in this unit is brachiopods, bryozoans, gastropods, trilobites, and receptaculites. The upper Dunleith contains numerous hardground horizons, one in every 5-20 cm interval. Its lower boundary is gradual, but commonly defined by a 1 cm-thick prominent shale parting. The upper boundary is extremely gradual, and is defined based on hardground occurrence, argillaceousness, and occurrence of large gastropod fossils (*Hormotoma major*, Fig. 22E).

The Wise Lake Member is a fine- to medium- crystalline dolostone with mudstone to wackestone textures, and is less porous than the upper Dunleith below, but the distinction is subtle. It is moderately bioturbated by 1-2 cm-wide *Thalassinoides* burrows. The fauna consists of small brachiopods less than 1 cm, large gastropods (*Hormotoma major*), and bryozoans. Terrigenous silt is less than 1% in this unit. Due to lack of continuous outcrop exposure, the correlation of measured sections was not made. Frequency of hardground occurrences

is often the only reliable tool for correlation. The thickness of Wise Lake Member is relatively continuous ranging 12-14 m.

The uppermost unit, the Dubuque Member is only observed in cores in the south (Waukesha, Racine, and Kenosha counties). It is characterized by abundant disseminated crinoid fragments and frequent dark brown argillaceous partings. Its thickness ranges from 2.3 m to 10 m (Appendix C). The brown partings are composed of clay seams rich in phosphate grains. The clay content gradually increases upward. Terrigenous silt is rare in this unit. This unit is scarcely bioturbated by rare 2-3 mm-wide horizontal burrows. This unit is overlain by the Maquoketa shale with a very sharp, probably erosional boundary.

4. CONODONT STUDY

Introduction

The Platteville Formation in eastern Wisconsin consists of dolostone and argillaceous dolostone. After the initial lithologic description by Chamberlain (1877), several workers have studied the lithostratigraphy and biostratigraphy of the Platteville Formation in eastern Wisconsin (Atkinson, 1971; Moretti, 1971; LoDuca, 1986). Atkinson (1971) and Moretti (1971) identified all three members of the Platteville Formation putting the McGregor-Quimbys Mill boundary at the contact between the slightly argillaceous dolostone unit below and the 4-6 m-thick argillaceous-free vuggy dolostone unit above. However, their correlation of the uppermost unit of the Platteville Formation in eastern Wisconsin to the Quimbys Member in southwestern Wisconsin is

problematic because their description of the uppermost Platteville unit is more like the lithology of the Nachusa Formation than the Quimbys Mill Formation in Illinois (Willman and Kolata, 1978). LoDuca (1986) described three members of the Platteville Formation in northeastern Wisconsin and included the uppermost vuggy, massive dolostone unit into Quimbys Mill Member. However, he did not describe the lower boundary of the Quimbys Mill Member nor mentioned clearly the lithological difference of the Quimbys Mill Member from the McGregor Member below. Careful investigation of his description reveals that the uppermost Platteville unit he described corresponds to the Nachusa Member and it thins northward. Conodont work has been done to find out probable miscorrelation.

In eastern Wisconsin, almost no sedimentological studies have been done for the Galena Formation except few studies including lithologic descriptions and brief environmental interpretation (Chamberlain, 1877; Ostrom, 1967b; Moretti, 1971; LoDuca, 1988). Moretti (1971) described a core extracted from Sheboygan County and identified the Spechts Ferry and Guttenberg members of the Decorah Formation, and above them Buckhorn and St. James members of the Galena Formation (Fig. 60). However, his identification of the Decorah Formation is problematic because according to his lithologic description, the interval he correlated to Decorah Formation seems to correspond to the Ion sub-member in this study which correlates to the Buckhorn and St. James members in Illinois (Fig. 60). LoDuca (1988) indicated that the Decorah Formation is absent in northeastern Wisconsin, and suggested that the lower shaly portion of the Dunleith

Member (Ion sub-member) correlates to the Decorah Formation, that is, he interpreted the lack of the Decorah Formation in eastern Wisconsin as a facies change. Conodont work has been done to solve these problems.

Platteville Formation

To correlate the uppermost unit of the Platteville Formation in eastern Wisconsin, Nachusa Member, with the Platteville members in southwestern Wisconsin one sample was taken from the uppermost bed of the Platteville Formation in Watertown Quarry, Locality 2 (Fig. 5). The identified species and the number of the specimens is shown in Table 4. These data are compared with Chen's unpublished description of the Platteville conodonts in southwestern Wisconsin, in which the vertical change in the abundance of each conodont species are shown in the samples taken from 21 horizons of the Platteville Formation (Table 5). The data suggests that the conodont species in Nachusa Member are more similar to upper McGregor Member than Quimbys Mill Member particularly in the occurrence of the species *Polyplacognathus ramosus*, *Plectodina aculeata*, and *Curtognathus sp.*, but the result is not conclusive because the specimens studied were collected from only one locality and the change in the conodont species is due to facies change rather than temporal change.

Atkinson (1971) studied conodont species in Wisconsin and compared Weber's (1966) Minnesota study in which he noted that the species *Oistodus venustus* does not extend above the top of the McGregor in Minnesota. Atkinson (1971) reported that this species

A.

Watertown Qr. (uppermost bed of the Platteville Formation) [U.W.1896/25]	
SPECIES (Assemblage Name)	NUMBER OF SPECIMENS
<i>Drepanoistodus suberectus</i> :	13 (N: 12, G: 1)
<i>Panderodus gracilis</i> :	7
<i>Phragmodus undatus</i>	5 (S: 4, P: 1)
<i>Belodina compressa</i>	1 (D: 1)
<i>Polyplacognathus ramosa</i>	1
<i>Plectodina aculeata</i>	1 (P: 1)
<i>Curtognathus sp.</i>	1
<i>Cordylodus sp.</i>	1

B.

Fort Atkinson Qr. (0.3 m above from the base of Galena Formation) [U.W.1896/26]	
SPECIES (Assemblage Name)	NUMBER OF SPECIMENS
<i>Phragmodus undatus</i>	16 (S: 16)
<i>Belodina compressa</i>	8 (A: 1, D: 7)
<i>Drepanoistodus suberectus</i>	20 (N: 18, G: 2)
<i>Polyplacognathus ramosa</i>	14
<i>Oistodus venustus</i>	1
<i>Belodina dimunitiva</i>	1
<i>Curtognathus sp.</i>	1
<i>Panderodus gracilis</i>	1
<i>Plectodina aculeata</i>	1

C.

Watertown Qr. (1 m above from the base of Galena Formation) [U.W.1896/27]	
SPECIES (Assemblage Name)	NUMBER OF SPECIMENS
<i>Phragmodus undatus</i>	16 (S: 10, P: 5, M: 1)
<i>Belodina compressa</i>	5 (A: 1, D: 4)
<i>Drepanoistodus suberectus</i>	5 (N: 4, G: 1)
<i>Polyplacognathus ramosa</i>	2
<i>Oulodus serratus</i>	2
<i>Curtognathus sp.</i>	1

Table 4. Identified conodont species in eastern Wisconsin. A, C: Locality 2. B: Locality 2. The numbers in the parenthesis represent the number of the specimens of the element. N: Non-geniculate element; G: Geniculate element; S: S-element; P: P-element, M: M-element; D: Denticulate element; A: Adenticulate element.

SAMPLE NO.	Drepanoistodus subercus		Phragmodus undatus			Panderodus gracilicis			Panderodus panderi			Polyplacognathus ramosus			Plectodina aculeata			Curtognathus sp.	Distacodus variabilis
	N	G	S	P	M	S	M	S	M	S	P	M	S	P	M	S	P		
F-21-82	24	6	17	6	8	6	6												
F-20-82	10	6	20	10	6			13											
F-19-82	7	1	19	9	8	1	4	2											
F-18-82			136	120	58	2	3	34											3
F-17-82	41	10	88	16		48	37											14	
F-16-82	5	1	4	1	8	1	4												
F-15-82	99	38	18	7	7	4	8	57					18	7					3
F-14-82	26	7				1	1	10	6			4	1						
F-13-82	14							3							2				
F-12-82																			
F-11-82	4	1				1	4	6											
F-10-82	32	5				6	4	11	3			2	1		12	6			
F-9-82	10	2				2	5	4							2				1
F-8-82	42	4				4	16	11	4			20	1		8	1			1
F-7-82	40	6				4	10	10	8			42			9	2			3
F-6-82	6	7				2	7	2	2			1							
F-5-82	9	2				1	1	4				1							1
F-4-82	19	3				5	5	2				5							
F-3-82	13	4				4	4	6				2							3
F-2-82	44	5				18	21	14				6							6
F-1-82	8	2				6	5	4				4							1

Table 5. Conodont species abundance in the Platteville Formation. The sample numbers are arranged from stratigraphically bottom to top. Data are from Chen's (1985) unpublished description on the conodont species from the Platteville Formation in southwestern Wisconsin. The conodont specimens and the data are stored in the Geology Museum in the UW-Madison. QM: Quimby's Mill Member; MG: McGregor Member; PC: Pecatonica Member. Compare the occurrence of the species *Polyplacognathus ramosus*, *Plectodina aculeata*, and *Curtognathus sp.* with those in Table 4.

MSAMPLE NO.	Stauferella falcatus		Belodina compressa		Oistodus venustus	Belodina diminutiva	Oulodus serratus			Cordylodus flexuosus	Erismodus gracilis	Ozarkodina concina
	S	A	S	P			P	S	M			
F-21-82			2									
F-20-82			1									
F-19-82			4									
F-18-82			6	3		1						
F-17-82			1		1		15	38	9	44	15	69
F-16-82												
F-15-82	2	16	42	6	9	2	4	6	4			
F-14-82	7		10									
F-13-82			11	3		3						
F-12-82			1									
F-11-82		1	6									
F-10-82	2	5	26		2	3						
F-9-82	1		11	4	1							
F-8-82	1	2	44	9	5							
F-7-82	2	5	27	7								
F-6-82		2	2	1								
F-5-82			6		1							
F-4-82		1	6		1							
F-3-82		6	10	1								
F-2-82	1	6	22	4								
F-1-82		3	9	1								

Table 5 (Continued).

ranges to the top of the Platteville Formation in Wisconsin and suggested that the Platteville Formation becomes younger in a westward direction. Within the state of Wisconsin, the species *Belodina dispensa* was not found in the northeast but is abundant in the southwest, which also support the younger-westward direction of the Platteville Formation in Wisconsin (Atkinson, 1971). No information is available of the range of the species *Belodina dispensa* in Minnesota because Weber (1966) incorporated *B. dispensa* with *B. compressa* . Although Atkinson (1971) interpreted the conodont species variation in Wisconsin as temporal ("most of the Platteville section had been deposited in the northeast before *Belodina dispensa* made its appearance"), it is interpreted in this study as erosional or depositional facies changes.

In conclusion, conodont work of the uppermost Platteville unit supports a correlation of Nachusa Member to the upper McGregor Member in southwestern Wisconsin and probably the Nachusa Formation in Illinois. The lack of Quimbys Mill Member in eastern Wisconsin probably resulted from erosion before the deposition of overlying unit or non-deposition or both. The unconformity surface found on top of the Platteville Formation in Fort Atkinson and Watertown quarries (Fig. 20) also indicate probable erosion of the Quimbys Mill Member in eastern Wisconsin.

Galena Formation

In eastern Wisconsin, the Decorah Formation only occurs south of Dodge County (Fig. 5, Appendix C). It is identified as the upper

Guttenberg Member based on the dark brown shaly partings and the dominant skeletal grainstone lithology. It is conformably overlain by the unit Ion sub-member, which is composed of skeletal grainstone interbedded with green shales. I have attempted to correlate the Ion sub-member to the strata in the southwestern Wisconsin by conodont species. Two samples were taken from the lower shaly beds of Ion sub-member in Fort Atkinson Quarry, Locality 1 and in Watertown Quarry, Locality 2, and the results are shown in Table 4.

The form species *Phragmodus undatus* (S-element in the *Phragmodus undatus* assemblage) is particularly abundant in the Decorah Formation (including the Ion Member; Atkinson, 1971; Clark and Babcock, 1971a). Clark and Babcock (1971a) described conodont species from six localities in southwestern Wisconsin, and listed the number of each species in three members of the Decorah Formation: the Spechts Ferry, Guttenberg, and Ion members. In their description the assemblage species, *Polyplacognathus ramosa*, shows great relative abundance in the Ion Member whereas it is almost absent in the Guttenberg Member (Table 6). Therefore, the abundance of *Polyplacognathus ramosa*, in the Ion sub-member is considered as a strong evidence that it corresponds to the Ion Member which is basal Galena Formation in Wisconsin. Besides the conodont evidence, the dominant grainstone lithology of the Ion sub-member distinguishes it from the Spechts Ferry Member of the Decorah Formation which consists of green shale with thin interbeds of lithographic limestone. It is also distinguished by the green color from the pinkish-brown Guttenberg Member which contains abundant phosphate grains.

FORM SPECIES	SF	Gut	Ion
<i>Polyplacognathus ramosa</i>	3		67
<i>Polyplacognathus bilobata</i>	2		43
<i>Prioniodina polita</i> ?	7	1	3
<i>Prioniodina sp.</i>			5
<i>Tetraprioniodus breviconus</i> ?			2
<i>Trichonodella sp.</i>		1	
<i>Zygognathus sp.</i>			1

Table 6. The number of specimens of each form species of the *Polyplacognathus ramosa* (assemblage name) showing the relative abundance in the three members of the Decorah Formation in southwestern Wisconsin. Compare with Table 6, B and C. SF: Spechts Ferry, Gut: Guttenberg. From Clark and Babcock (1971a).

In conclusion, only upper part of the Decorah Formation occurs in eastern Wisconsin and it thins out to the north in Jefferson County. Therefore, significant time of nondeposition existed between the Platteville and Galena formations in eastern Wisconsin, probably due to exposure of the Wisconsin Arch during Decorah time. Renewed marine transgression over the Wisconsin Arch resulted in gradual onlapping of the Decorah sediments to the north.

III. COMPONENTS

1. ORGANIC COMPONENTS

The most abundant organic components are: brachiopods, bryozoans, and crinoids. Most identifiable brachiopods occur as external or internal molds. Brachiopod moldic porosities are locally abundant. Large bryozoan fragments were recognized by the shape of the zooecia and wall structure. Crinoid columnals occur as body fossils and external molds.

Gastropods, trilobites, and pelecypods are also common fauna and locally abundant. Cephalopod molds are occasionally observed. Ostracods have been reported in the Sinnipee Group (Willman and Kolata, 1978; Delgado, 1983a; Bakush, 1985), but it is very difficult to identify them with certainty in dolomite due to lack of sweeping extinction in thin section under microscope. Receptaculites (a Dasycladacian Green Algae) are abundant at particular intervals of the Galena Formation. Occasional bloom of their occurrence might be related to warmer period (Nitecki, 1972).

Rugose corals occur as internal or external molds. Many species of conodonts are also identified in the upper Platteville and lower Galena formations.

Fragments of those organic components are abundant throughout the Sinnipee Group. Two types of bioclasts are recognized: Type A bioclasts are sand-sized, highly fragmented, and generally pyrite-stained; Type B bioclasts are pebble-sized, non-stained by pyrite, and

generally retain original shape and articulation. The bioclasts seems to have two sources. The type A bioclasts are interpreted to have derived from skeletal shoals, which might have existed landward from the depositional site. This interpretation is based on the good sorting and taphonomic characteristics of the bioclasts; highly fragmented, disarticulated bioclasts indicate longer time exposure in the high energy environments (Brett and Baird, 1986). The taphonomic criteria also suggest that Type B bioclasts are indicative of episodic, rapid deposition under high energy (Brett and Baird, 1986). The type B bioclasts might have derived autochthonously, by concentration of shells of living and dead organisms from the sea floor, as well as exhuming previously buried shells. This mechanism is suggested by many workers as the origin of the storm-generated bioclastic deposits (Specht and Brenner, 1979; Kreisa, 1981; Miller et al., 1988). The pyrite staining seems to be related with long time exposure of bioclasts on sea floor. The pyrite mineralizations on the hardground surfaces probably have similar origin.

2. INORGANIC COMPONENTS

Quartz Sand Grains

Quartz grains are particularly abundant in the Glenwood Member and the lower Platteville Formation, as well as the eolian sandstone beds of the St. Peter Formation. The quartz sand grains occurring in the Sinnipee Group are medium- to coarse-grained and disseminated as 'floating' grains. Although it is not clear how the sands were

introduced, present 'floating' texture is probably due to bioturbation. Table 4 shows the variation of the quartz grains with textures and abundances.

Terrigenous Silt

Terrigenous silt is common in most of the Galena Formation and in some intervals of the Platteville Formation (Table 7). They are particularly abundant in the lowermost Galena Formation (Ion Sub-member). They are well sorted, subangular to subrounded silt-sized grains of quartz and feldspar. The relative proportion of feldspar grains is 10-20%. The feldspar includes microcline and plagioclase but identification of silt-sized orthoclase grains is impossible under petrographic microscope. The feldspar grains are mostly euhedral, show the characteristic rhombohedron shape. Some quartz grains are also euhedral and show bipyramidal shape. In general, the silt grains are richer in argillaceous units (Mifflin Member, Ion Sub-member) and are concentrated in clay seams and hardgrounds in microscopic scale.

The higher concentration of the terrigenous silt in the clay seams can be explained as either depositional or diagenetic. If the terrigenous silt supply is constant and the clay seams represent time intervals of low sedimentation rate, the silt could be concentrated. An alternative setting interprets silt to be concentrated diagenetically along the clay seams as insoluble residue during burial (Wanless, 1979). However, the higher concentration of the silt along the hardgrounds, which also represent low sedimentation rate, seems to suggest a depositional setting and represent decreased carbonate or an increased clay

FORMATION	SUBDIVIDED UNIT	GRAIN SIZE	ROUNDNESS	SORTING	PROPORTION
GALENA	Dubuque	Silts	Sub-A to Sub-R	Good	Rare
	Wise Lake	Silts	Sub-A to Sub-R	Good	<1%
	Dunleith (upper)	Silts	Sub-A to Sub-R	Good	<1%
	Dunleith (lower): Ion Sub-member	Silts/ M-C Sands	Sub-A to Sub-R/ Well Rounded	Good/ Good	1-20%/ <1%
	GUTTENBERG	Silts	Sub-A to Sub-R	Good	Rare
DECORAH	Nachusa	Silts	Sub-A to Sub-R	Good	<1%
	Grand Detour				None
	Mifflin	Silts/ M-C Sands	Sub-A to Sub-R/ Sub-A to R.	Good/ Moderate	<1%/ <1%
PLATTEVILLE	Pecatonica	M-C Sands	R. to Well R.	Good	<10%
	Sandy dolostone	M-C Sands	Well Rounded	Moderate to good	<50%
	Dolomitic Ss.	F-C Sands	Sub-R to Well R.	Poor to Moderate	>50%
	Massive Ss. --poorly Sorted	F-C Sands	Sub-R to Well R.	Poor	90-100%
	_Md. Sorted	M-C Sands	Well Rounded	Moderate	90-100%
ST. PETER	Laminated Ss.	F-M Sands	Well Rounded	Very good	99-100%

Table 7. Textures and abundances of quartz grains in the Sinipee Group in E. WI.

sedimentation rate.

The terrigenous silts were probably transported by winds considering extreme good sorting and great lateral continuity of silty beds (Delgado, 1983a). Delgado (1983a) reported the composition of the terrigenous silts (99% quartz, 1% microcline) and suggested that they were derived from a supermaturely weathered source terrane, an emergent source area 250-500 miles north to west of upper Mississippi Valley. He also states that one problem with an "eolian" interpretation is that of paleowind direction. If the Wisconsin arch lay in 10-20°S (Witzke, 1980), with the paleoequator running roughly NE-SW, the prevailing trade winds should not have blown from the present north, northwest, or west.

Delgado's paradox is probably derived from the misidentification of the silt-size minerals. In my approximation, the proportion of feldspar minerals reaches up to 20% although point-counting was not done. Under petroscopic microscope, silt-sized plagioclase grains are easily mistaken as quartz because they are too small to show the characteristic plagioclase twins. Moreover, it is almost impossible to distinguish K-feldspar except microcline from quartz. Careful comparison of the two minerals with other features such as roundness, cleavage, sweeping extinction, or crystal habit will only help to tell them apart. Staining method will be useful. Therefore, according to the composition and textures of the silt grains, the source area could be either Taconic Island or supermature terrains such as Canadian Shield. The occasionally intercalating bentonite beds in the Galena Formation suggest that the prevailing wind direction during Galena time was

paleosoutheast. The Taconic Island was a volcanic magmatic arc locating to the paleosoutheast and provided large amount of volcanic ash. Ross (1976, Fig. 9) also suggested the same paleowind direction.

Clay

Two types of clay are recognized in this study: green and dark brown clay. The first type occurs from the Glenwood Member to the Dunleith Member. The second type characterizes the uppermost Galena Formation (Dubuque Member).

The lateral variation of the amount of clay and the thickness of the shale seems to be related to the proximity to the source area of the siliciclastics. This generalization is based on the assumption that all the laterally equivalent beds were deposited under same hydraulic energy (e.g., below FWB). So, it can not be applicable to the stratigraphic intervals that show significant lateral facies change caused by changes in energy regime. The green clay content in the lower Galena Formation (Dunleith Member) gradually but noticeably increases northward, which may indicate that the major source of the green clay of the Galena Formation is probably the Canadian Shield to the north. The source area of the green clay in other intervals where lateral change is not observed is not clear. The dark brown clay occurs in the Dubuque Member with a gradual increase upward and was probably derived from the Taconic Island, which supplied much siliciclastics with decreasing grain size westward in Late Ordovician as sea level increased (Dott and Prothero, 1994). Witzke and Kolata (1989) also noted the widespread brown shale in the uppermost Galena Group

(Dubuque Formation) in the upper Mississippi Valley is dissimilar to any known shale in the Galena Group but is largely indistinguishable from many shales in Maquoketa Formation. They suggested that green shales in the Platteville and Galena groups were derived from the Transcontinental Arch whereas the Maquoketa shales were derived from distant eastern sources associated with uplift of the Taconic orogen.

Phosphate Grains

There are two types of phosphate grains. The first type is abraded inarticulate brachiopod fragments with variable size ranging from 0.05 mm to 0.5 mm. This type occurs as a minor constituent throughout the Sinnipee Group with subtle change in amount. The other type is probably inorganic phosphate, characterized by spherical grains ranging from 0.02 mm to 0.05 mm. This type is particularly abundant in four intervals: Glenwood Member, lower Mifflin Member, Guttenberg Member, and Dubuque Member. The high concentration of phosphate grains seems to be related with low sedimentation rate.

Intraclasts

Intraclasts are defined as reworked fragments of a penecontemporaneous sediment (usually weakly consolidated) that has been eroded within the basin of deposition (Bates and Jackson, 1980). Two types of intraclasts are recognized. Type A intraclasts are variable in composition ranging from mudstone to grainstone. They are mostly platy and discoidal in shape and are always stained by pyrite to dark gray to black color. Type A intraclasts occur throughout the

Sinnipee Group in the thin-bedded grainstone lithofacies. Type B intraclasts are composed only of carbonate mudstone and restricted in occurrence to the Mifflin Member. They are irregular but spherical to sub-spherical in shape, and commonly are not stained or stained only at the edge by pyrite. The Type A intraclasts were probably derived from hardgrounds, which is evidenced by the borings and the pyrite staining in the intraclast as in the hardgrounds. Type B intraclasts might be derived from the early formed nodules considering the close relationship of the intraclasts and the associated lithology below.

Peloids

0.2-1.0 mm-sized spherical grains (?) are observed in the lower Platteville Formation but their identity as grains is usually not clear enough to be distinct from dark zoning in dolomite crystals. Moreover they could be pseudo-peloids (small-sized intraclasts). Therefore the occurrence of true pellet is not certain.

IV. LITHOFACIES DESCRIPTION & INTERPRETATION

Ten lithofacies are defined on the basis of field descriptive features such as major skeletal components, sedimentary structures, and textures. Additional information derives from rock slabs and thin sections.

The ten lithofacies are:

- 1 Laminated sandstone lithofacies (LS)
- 2 Massive sandstone lithofacies (MS)
- 3 Shale lithofacies (Sh)
- 4 Sandy carbonate lithofacies (SC)
- 5 Skeletal wackestone to packstone lithofacies (SWP)
- 6 Mudstone lithofacies (Md)
- 7 Nodular carbonate lithofacies (NC)
- 8 Thin-bedded grainstone lithofacies (TBG)
- 9 Porous dolostone lithofacies (PD)
- 10 Crinoidal wackestone lithofacies (CW).

Dunham's (1962) limestone texture is the primary criteria in defining these lithofacies. However, some lithofacies are named on the basis of their lithologic composition. For example, the nodular carbonate lithofacies represent mudstone- to wackestone-textured argillaceous limestone/dolostone with cm-scale irregular argillaceous partings. Diagenetic lithofacies name is used when the original depositional textures are difficult to discern due to pervasive dolomitization (e.g., porous dolostone)

Table 2 summarizes the major characteristics and interpreted

depositional environments of the lithofacies from the St. Peter Formation to the top of Galena Formation in eastern Wisconsin.

1. LAMINATED SANDSTONE (LS)

Description

This lithofacies occurs in the St. Peter Sandstone and outcrops in Dane County the Markesan and Ripon quarries (Locality 12, 14) in Fond du Lac County. It consists of fine- to medium-grained quartz-arenite and is characterized by fine, parallel lamination and several m-thick cross-beds. The angle of the cross bedding is mostly less than 20° but some reach up to 46° (Figs. 9, 28). Its color is light yellow to greenish yellow or light brown. No bioturbation is observed in this lithofacies. The quartz grains are moderately to well sorted and very well rounded.

Interpretation

Based on the fine, laterally continuous parallel-lamination and large-scale cross bedding, this lithofacies is interpreted to have deposited in eolian environments. Winfree (1983) and Long (1988) reported adhesion ripples which is typical of eolian deposits in similar lithofacies in southwestern Wisconsin.

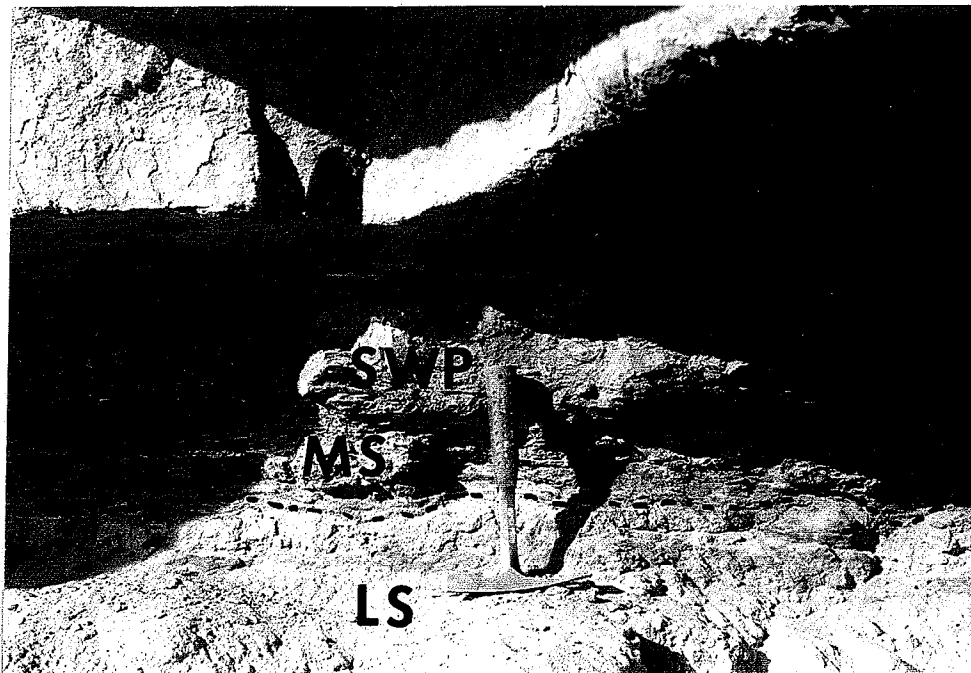


Fig. 28. Field photograph of the laminated sandstone lithofacies (LS) showing high angle cross-lamination and the overlying massive lithofacies (MS) of the Glenwood Member. The Glenwood Member is overlain by the skeletal wackestone to packstone lithofacies of the Chana sub-member. Note the jagged boundary (dashed line) between the two units. Markesan Qr., Locality 12.

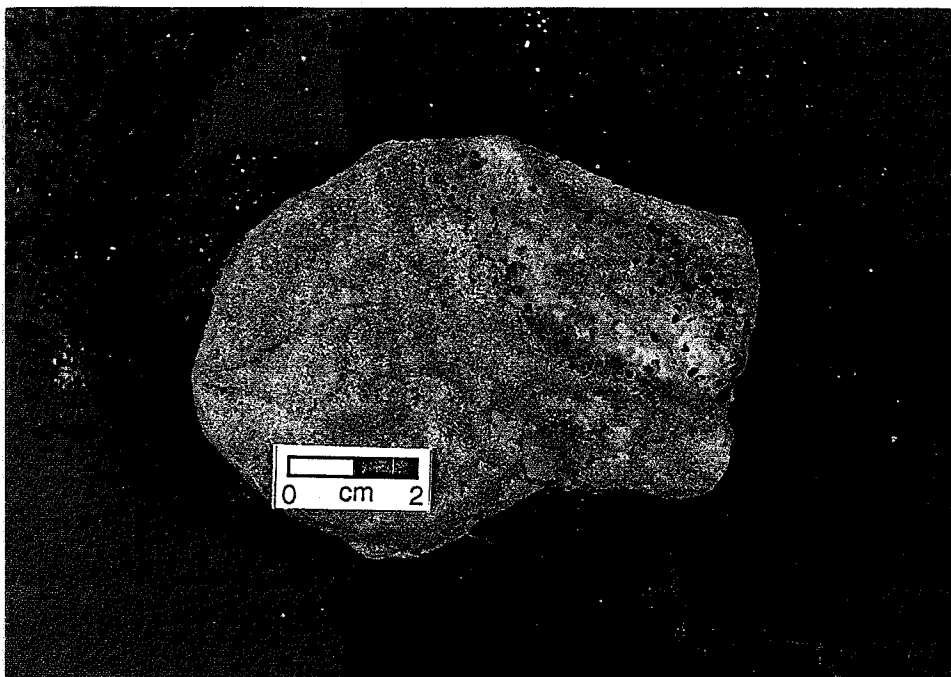


Fig. 29. Rock slab photograph of moderately sorted massive sandstone containing silicified oolitic grainstone pebbles reworked from the Prairie du Chien Group. The sample is taken from the base of the Glenwood Member at Sun Prairie Qr., Locality 17 [U.W.1896/3].

2. MASSIVE SANDSTONE (MS)

Description

This lithofacies sharply overlies the laminated sandstone lithofacies with jagged boundary (Fig. 28). It is sharply overlain by sandy carbonate lithofacies with or without intervening dark green shale. The lithology ranges from a moderately to well-sorted quartz-arenite to a poorly sorted quartz-arenite. The well-sorted sandstone consists of medium- to coarse-grained, well-rounded quartz grains and in places contains at the base 1-6 cm-sized pebbles of silicified oolitic grainstone (Fig. 29). *Chondrites* burrows are rarely observed in rock slabs of this lithology but most outcrop surfaces appear massive without traces of burrowing due to poor exposure. It is observed in outcrops of northern study area from Dane County to Fond du Lac County.

The poorly sorted sandstone consists of mixture of fine- to coarse-grained quartz grains with minor green clay and commonly contains 1-5 mm-sized phosphate grains. Fine sand-sized microcline and hornblende grains are also present as accessory minerals. *Chondrites* burrows are common in this lithology. It only occurs in southeastern area from Racine County to Kenosha County.

Interpretation

The bioturbated nature of this lithofacies clearly indicates deposition in a marine environment. The sharp lower contact probably represents a ravinement surface that is indicated by the conglomeratic

lag with well-cemented clasts (Long, 1988). The well-sorted sandstone might be deposited just below shoreface while the poorly sorted sandstone was probably deposited at deeper water depth.

3. SHALE (Sh)

Description

The shale lithofacies in the Glenwood Member occurs as several 10's of cm thick beds in cores in Kenosha County, and as less than 1 cm-thick dark brown shale laminae containing abundant phosphate grains north of Kenosha County. The shale is dark green in color and very fissile (Fig. 30). It is correlated over much of the study area although the shale lithofacies contains some intercalating medium-grained quartz sand lenses up to 1 cm thick. Burrows are common to abundant in these lenses and extend into adjacent shale. The proportion of the sandstones gradually increases upward until the clay occurs as mm-thick, dark brown laminae (continuous and discontinuous) in the dolomitic sandstone of the sandy carbonate lithofacies.

The shale lithofacies is also present in the basal Galena Formation. It mostly occurs as mm- to cm-thick green shale partings between the associated thin-bedded grainstone lithofacies in the southern study area. It is characterized by abundant skeletal fragments and fossils that are best observed on bedding plains. It is moderately to strongly bioturbated by mm-wide semi-horizontal burrows which extends into underlying grainstone beds (Fig. 31). The beds and bed thickness of this lithofacies within the same stratigraphic interval

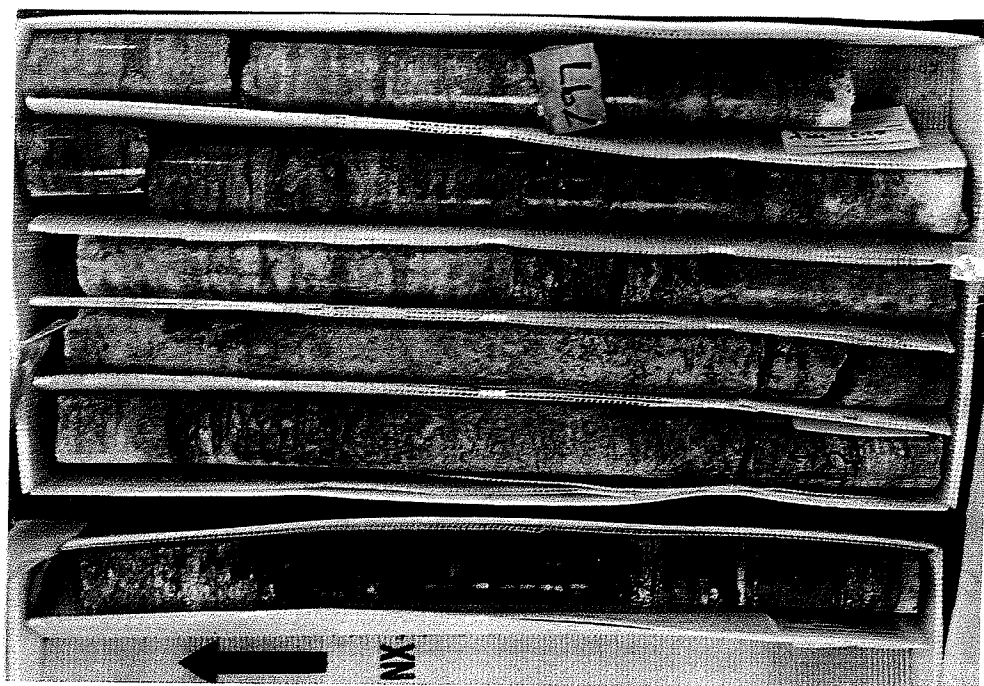


Fig. 30. Cores from Locality KE (see Fig. 5), Kenosha County, showing the shale lithofacies gradationally overlain by the pervasively bioturbated dolomitic sandstone. The intercalating sandstone lenses within the shale lithofacies are also bioturbated. The cores are 5 cm wide. WGNHS Sample Repository BD321, 807'-797'.

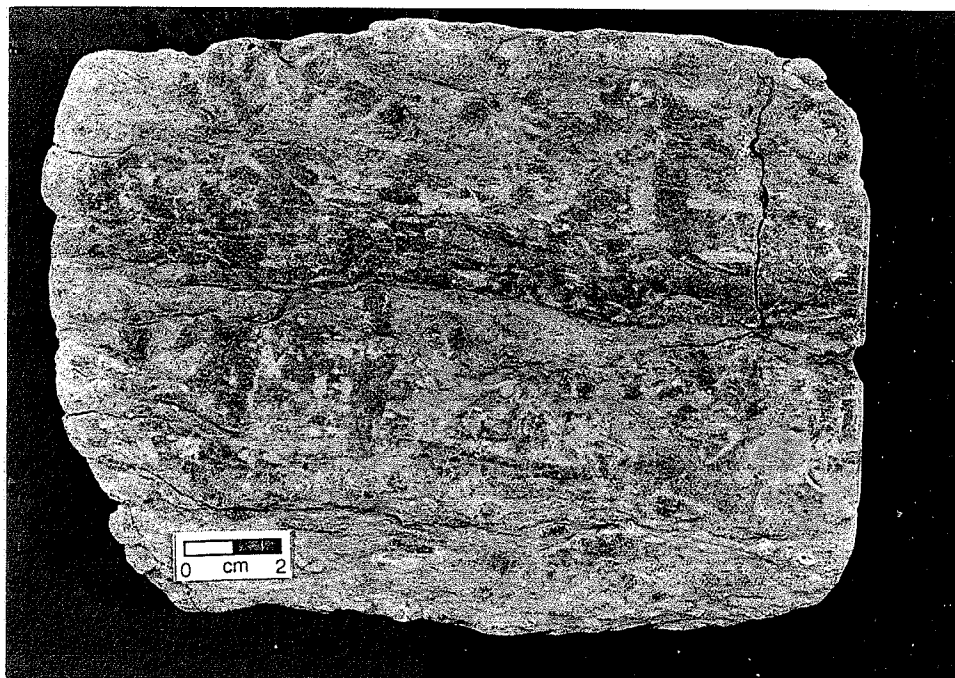


Fig. 31. Rock slab photograph of bioturbation mixing shale lithofacies (yellowish-green) and grainstone lithofacies (gray). Often the bioturbation is so intense that both lithofacies are completely mixed (see Fig. 49). When bioturbation is weaker, grainstone beds show few shale-filled burrows (see Fig. 48). Ion sub-member at Fort Atkinson Qr., Locality 1 [U.W.1896/4].

gradually increase to the north in the study area. The northward increase of argillaceousness is also reflected on the gradual decrease in the clay content to the south in the associated lithofacies.

Interpretation

Terrigenous clay, which comprises shale, is deposited below fair-weather wave base wherever there is available clastic input. However, if there is healthy production and accumulation of lime mud in mid-ramp the clay is diluted in this region and only it accumulates to shale where the lime mud input is very low which is approximately below storm wave base during Paleozoic. The thickness of shale beds seems to be related with the proximity to the source area as well as depth of deposition, that is, it accumulates thicker in the area closer to the source area if other factors such as carbonate productivity and energy condition are assumed to be the same. Therefore, the shale lithofacies in the Glenwood Member is interpreted to have been deposited below FWB, and probably below SWB because it is relatively thick, and lacks intercalating storm deposits except the upper part.

The shale lithofacies in the basal Galena Formation might have been deposited in a mid-ramp below FWB, but above SWB because it mostly occurs as thin shale partings and contains abundant skeletal grains and burrows indicating oxygenation, and it is intercalated by abundant storm beds. The occurrence of relatively thick shale beds in the northern area is probably due to their closeness to the source area.

4. SANDY CARBONATE (SC)

Description

This lithofacies comprises the uppermost Glenwood Member. It gradationally overlies the shale lithofacies or sharply overlies the massive sandstone lithofacies with intervening dark brown shale. It is composed of dolomitic quartz-arenite to quartz-dolomitic, fossiliferous mudstone to wackestone. The dolomitic sandstone occurs in the southern study area (Kenosha, Racine, Waukesha counties) while the sandy dolostone occur in the northern study area (Jefferson, Dodge, Fond du Lac counties).

The quartz grains are the most abundant component making more than 51% of the volume of the rock (dolomitic sandstone), but sometimes they comprise 31%-51% of the volume (sandy dolomite). Quartz grains are coarse- to medium-grained, well-rounded, and poorly to well sorted with increase in the sorting generally upward and to the north of the study area. Zircon and hornblende grains are accessory minerals rarely observed. Sand-sized phosphate grains are common throughout this lithofacies and they are particularly abundant in the dark brown shale streaks at base (Fig. 32). Sand grains are in grain contact and sometimes show sutured boundaries (Fig. 33). The spaces between the grains are filled with fine-crystalline xenotopic dolomite crystals. The carbonate content gradually increases upward until the quartz grains are floating within carbonate matrix in the overlying bioturbated skeletal wackestone to packstone lithofacies of the Platteville Formation. Bioturbation is pervasive by abundant *Chondrites*

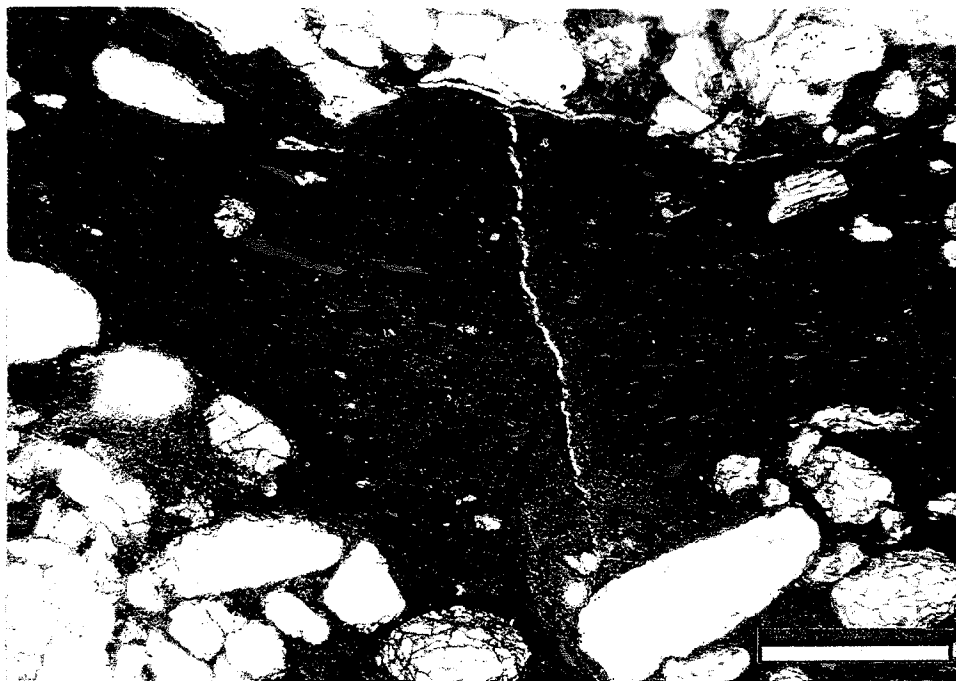


Fig. 32. Photomicrograph of the sandy carbonate lithofacies. The sample is taken from the base of the sandy carbonate lithofacies containing many shale streaks. Note the laterally elongated phosphate grains due to compaction. Scale bar is 0.5 mm long. PPL. Locality RA, Racine County [U.W.1896/17].

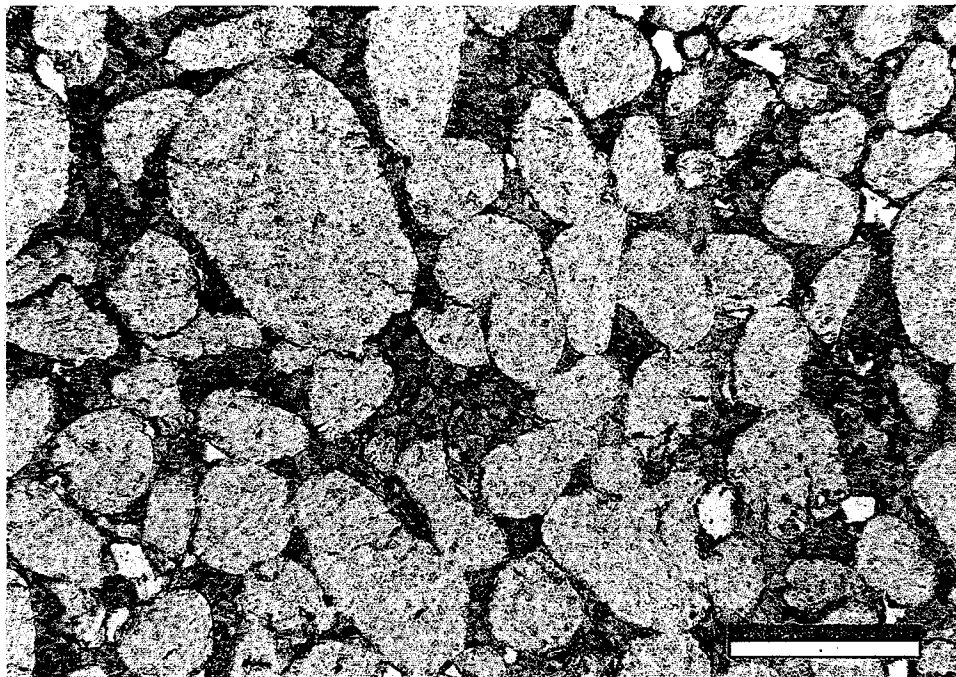


Fig. 33. Photomicrograph of the sandy carbonate lithofacies showing sutured boundaries between quartz grains. PPL (plane-polarized light). Scale bar is 0.5 mm long. Locality RA, Racine County [U.W.1896/18].

and common *Thalassinoides* burrows. Many ferruginous hardgrounds are present in association with these burrows. They are more common in the upper part of this lithofacies.

Interpretation

The sandy carbonate lithofacies is interpreted to have deposited in a marine environment around or just below FWB based on the high sand content and lack of current structure. The sedimentation rate was very low which is indicated by pervasive bioturbation and occurrence of many hardgrounds. The burrowed and Fe-mineralized surfaces are hardgrounds or firmgrounds formed during periods of non-deposition. The origin of the ferruginous hardgrounds is discussed later.

The sutured grain contacts of the quartz sand imply that the dolomite crystals filling the space between the quartz grains were originally matrix rather than cement or at least indicate that the grains were not cemented early. The fine size and dusty appearance of the dolomite crystals also suggest matrix texture. This idea is also supported by the fact that the dolomite crystals filling the burrows, which were originally lime mud, are identical to the matrix in crystal size and texture.

Therefore the sandy carbonate probably was deposited with discontinuous quartz sand input by longshore current with varying intensity into areas at or below FWB that was also characterized by very low rate of lime mud accumulation and strong bioturbation.

The increase in carbonate content upward with decreasing sand content indicates decrease in siliciclastic input into the basin or

increase in carbonate production or both. The decrease in siliciclastic input was probably caused by inundation of source area.

5. SKELETAL WACKESTONE TO PACKSTONE (SWP)

Description

This lithofacies occurs in the lowermost (Fig. 7) Platteville Formation (Type 1) and in the middle Galena Formation (Type 2). The texture of the skeletal wackestone to packstone lithofacies is that of a fine- to medium-crystalline dolostone in which the crystal size reflects original texture. It is strongly to pervasively bioturbated by horizontal to subhorizontal *Chondrites* burrows (Figs. 34, 36). The insides of the burrows are filled with mud that is fine to very fine crystalline dolomite. The sizes of the burrows are 3-5 mm in diameter.

The skeletal wackestone to packstone lithofacies (Type 1) is the most argillaceous-free carbonate unit in the Platteville Formation and is the most densely bioturbated unit in the whole Sinnipee Group. It is medium- to thick-bedded with very thin argillaceous partings. It is medium to dark gray in color with light gray burrow mottlings. The main constituents of this lithofacies are medium to coarse sand-sized bioclasts such as crinoids, bryozoans, and trilobites, which are often stained to dark gray with pyrite. This lithofacies shows gradual upward decrease in bioclast content in the southern study area (Racine, Kenosha counties) whereas it shows slight upward increase to the north of these counties. In general, this lithofacies within the same unit shows a north to south lateral change in texture from packstones

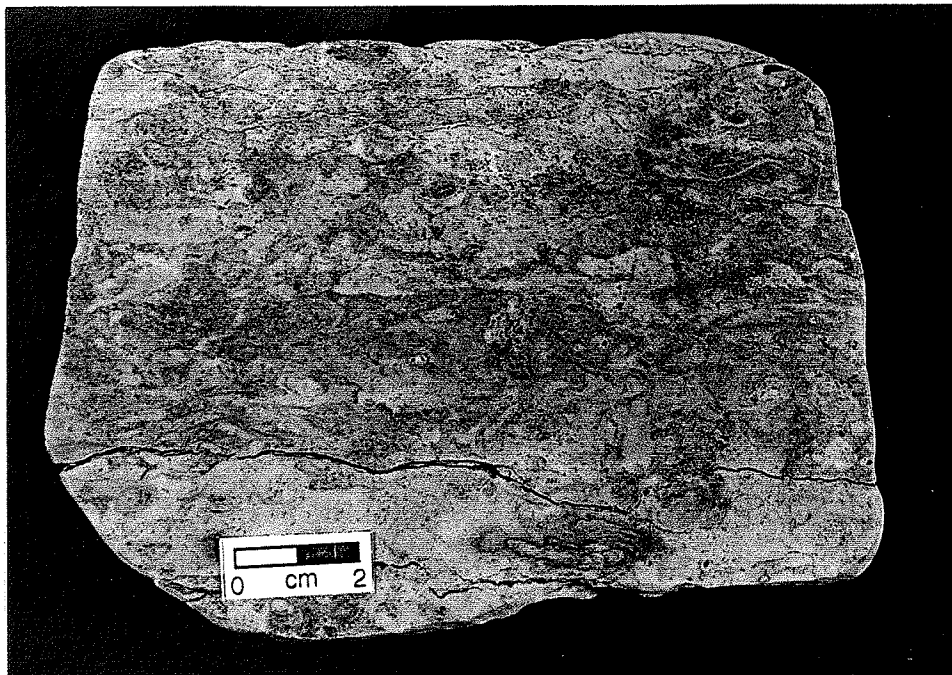


Fig. 34. Rock slab photograph of the skeletal wackestone to packstone lithofacies (Type 1) showing abundant 3-7 mm-wide *Chondrites* burrows filled with carbonate mud. The dark speckles are bioclasts, mostly of crinoids. Taken from the Chana sub-member at Ripon Qr., Locality 14 [U.W.1896/5].

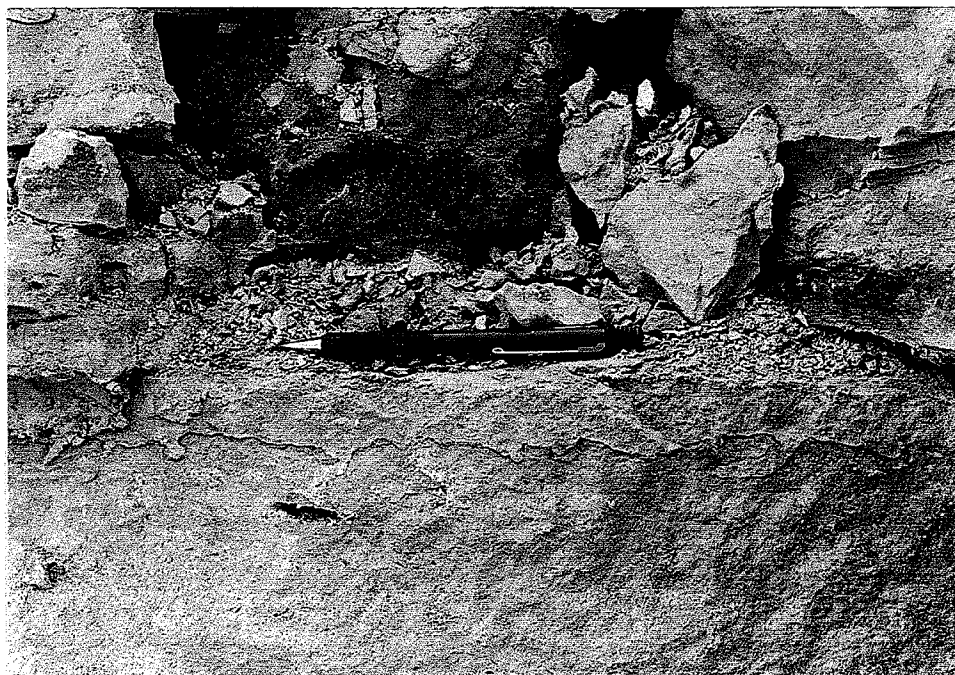


Fig. 35. Field photograph of the skeletal wackestone to packstone lithofacies (Type 1) showing a ferruginous hardground below pencil. Pencil for scale is 14 cm long. Top of the Chana sub-member at Sun Prairie Qr., Locality 17.

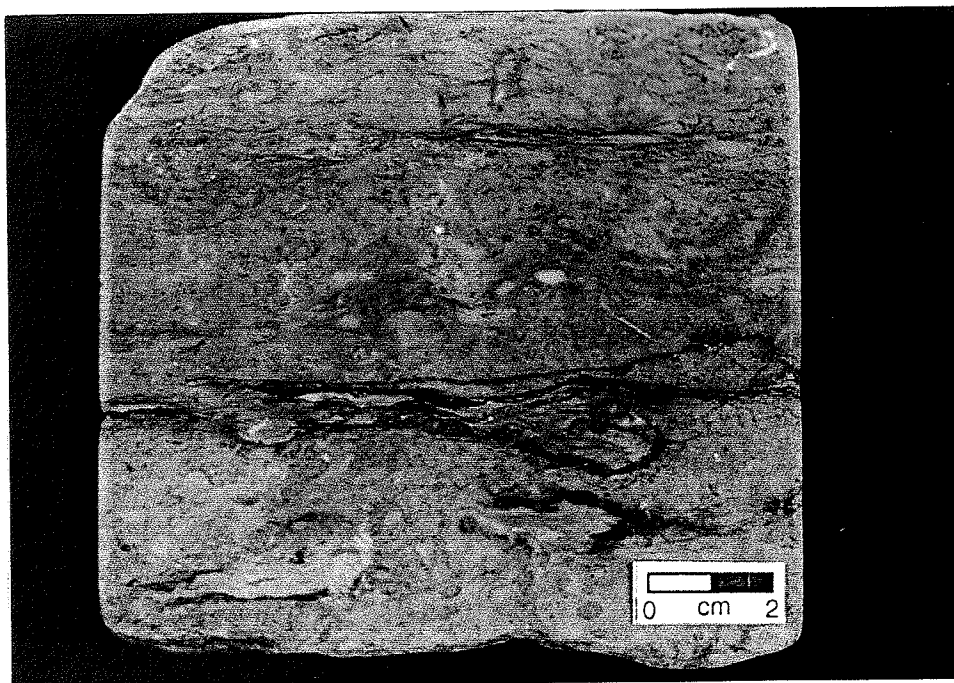


Fig. 36. Rock slab photograph of the lithofacies SWP (Type 2) showing 3-5 mm-wide *Chondrites* burrows filled with bioclasts or carbonate mud. Note 1 cm-wide *Thalassinoides* burrows associated with the ferruginous hardground. From the Wise Lake Member, Spruce Qr., Locality 7 [U.W.1896/6].



Fig. 37. Field photograph of the lithofacies SWP (Type 2) showing two hardground horizons (base and top of the bed) and associated *Thalassinoides* burrows. Marker pen for scale is 14 cm long. From the Wise Lake Member, Spruce Qr. Locality 7.

to wackestones. The texture is rather constant within a bed. This lithofacies usually contains medium- to coarse-grained floating quartz grains. The proportion of quartz grains gradually decreases from 10% at base to less than 1% at top. The quartz grains are very well rounded and generally concentrated outside burrow walls. Phosphate grains with 0.2 mm size and quartz silt are also common as minor constituents. Ferruginous hardgrounds are common in the lower and upper parts of this lithofacies and can be correlated widely within the study area (Fig. 34; Appendix B).

Skeletal wackestone to packstone lithofacies is also abundant in the middle Galena Formation (Type 2) in the northern study area (Dodge, Fond du Lac counties). It is carbonate to moderately argillaceous, fine- to medium-crystalline bioturbated dolostone (Fig. 36). Its texture is generally wackestone dominated and the texture is relatively variable within a bed compared to Type 1 SWP lithofacies. It is fine- to thick-bedded mainly depending on clay content. The clay content in this lithofacies varies laterally from outcrop to outcrop as well as vertically. However, there is a gradual northward increase in clay content in the study area. The color of this lithofacies (Type 2) is light purplish-gray to purplish-brown in carbonate beds and greenish-gray in argillaceous beds. This lithofacies is characterized by abundant ferruginous hardgrounds occurring repeatedly in 5-20 cm interval (Fig. 7). *Thalassinoides* burrows are usually associated with these hardgrounds (Figs. 36, 37).

Interpretation

A mid-ramp setting is interpreted for the deposition of the skeletal wackestone to packstone lithofacies. Considering the high fragmentation, good sorting of the skeletal grains, and relatively packstone-dominated texture without much vertical change, the Type 1 SWP lithofacies in the northern study area was deposited just below FWB. The sand-sized bioclasts were transported from shoal area by occasional storm-driven gradient current (Aigner, 1985). During normal weather condition, the depositional area was favored by lime mud accumulation and complete bioturbation homogenized the sediments obliterating the original sedimentary structures. The type 1 in the southern study area seems to have been deposited in a relatively deeper environment considering the texture.

A generally deeper mid-ramp setting is interpreted for the deposition of the Type 2 SWP lithofacies because of its wackestone-dominated lithology and more variable texture within a short interval than the Type 1.

6. MUDSTONE (Md)

Description

Mudstone lithofacies occurs as very fine-crystalline dolostone with variable amount of argillaceous material. It is thin- to medium-bedded with 0.1-1.5 cm-thick diffuse argillaceous partings. It occurs in three intervals in the Sinnipee Group: Pecatonica Member (Type 1), Grand Detour Member (Type 2), and Wise Lake Member (Type 3).

Mudstone lithofacies in the three intervals are distinguishable based on the amount of impurities, degree of bioturbation, and bioclast content.

The mudstone lithofacies in the upper Pecatonica Member (Type 1) comprises the Dane sub-member (Willman and Kolata, 1978). Its color is purplish-brown to greenish-gray with dark gray mottlings (Figs. 13, 15). It is slightly to moderately argillaceous with 0.5-1.5 cm-thick argillaceous partings. The clay content gradually decreases upward with increasing bed thickness (Fig. 15). The bedding planes are wavy and irregular and truncates underlying beds particularly in the lower part of the Dane sub-member. It is weakly to strongly bioturbated by 2-9 mm-wide mottled burrows. The intensity of bioturbation gradually increases to the south. The fauna in this lithofacies is brachiopods, crinoids, gastropods, and pelecypods.

The mudstone lithofacies in the Grand Detour Member (Type 2) is subdivided into two sub-types according to the degree of bioturbation and slight difference in clay content. The first sub-type is medium gray in color and moderately to pervasively bioturbated by 3-5 mm-wide dark gray mottled burrows (Fig. 38). The thickness of the first sub-type is 0.4-2.5 m. The second sub-type is light purplish-brown in color and rarely to weakly bioturbated by horizontal burrows less than 0.5 cm in diameter (Fig 39). It is occasionally intercalated with 0.5-1 cm-thick bioclastic grainstone lenses. The thickness of the second sub-type is 6-7 m. The first sub-type is slightly more argillaceous than the second. Fauna in the mudstone lithofacies in Grand Detour Member mostly occurs as whole fossils including brachiopods, gastropods, bryozoans, and rugose corals.

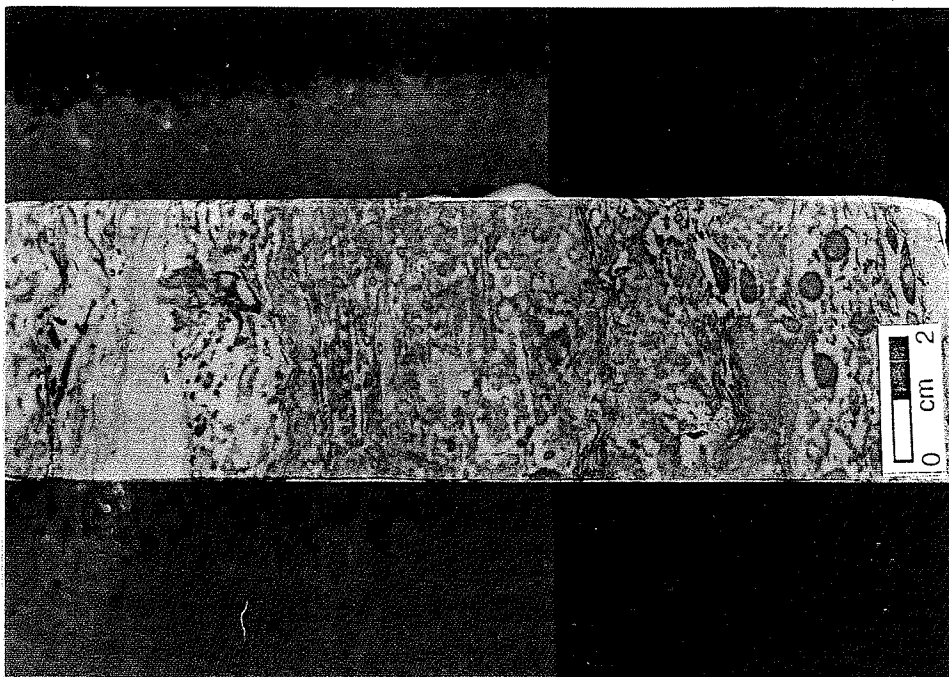


Fig. 38. Core slab photograph of strongly bioturbated Type 2 mudstone lithofacies. Note 3-6 mm-wide dark gray-mottled *Chondrites* burrows. Up to the left. Grand Detour Member. Locality JE, Jefferson County. WGNHS Sample Repository BD323, 254'.

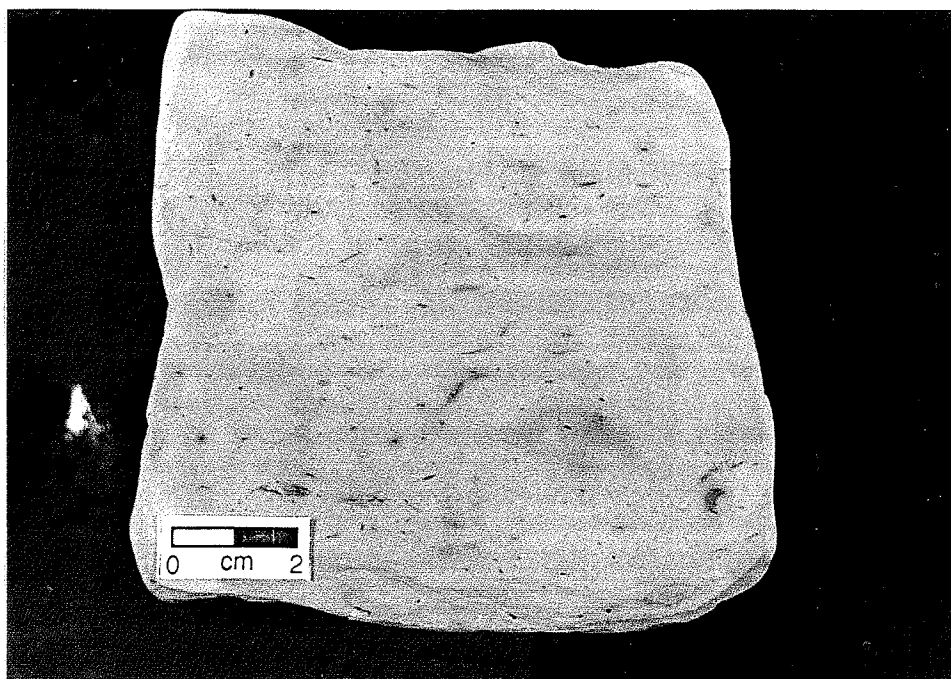


Fig. 39. Rock slab photograph of non- to weakly bioturbated Type 2 mudstone lithofacies. Note a few 1-2 mm-wide burrows. Grand Detour Member. Ripon Qr., Locality 14 [U.W.1896/7].

The mudstone lithofacies in the Wise Lake Member (Type 3) is relatively argillaceous-free to slightly argillaceous. The mudstone lithofacies in this interval rarely exceed 1 m in thickness without grainstone beds. It is strongly bioturbated by 0.5 mm-wide horizontal burrows which are sometimes filled with fine bioclasts. It is thin-bedded with thin gray argillaceous partings. This lithofacies commonly has intercalated bioclastic grainstone beds, which are mostly less than 5 cm in thickness.

Interpretation

The very fine-crystalline dolomitic mudstone is thought to have been originally lime mud or mudstone. Pervasive dolomitization has changed this lithofacies into the very fine-crystalline dolostone.

The origin of lime mud still remains a major problem in carbonate sedimentology specially in the Paleozoic. Many origins have been suggested as the sources of lime mud. They include direct precipitation from marine waters (Kinsman and Holland, 1969), production by disintegration of calcareous green algae (Neumann and Land, 1975), and/or breakdown of skeletal organisms other than plants (Matthews, 1966).

Although it is popularly believed that the algae are the producers of most, if not all, of the Recent carbonate sediments, there have been growing evidences for direct precipitation of lime muds from sea water based on geochemical data (Steinen et al, 1988; Robbins and Blackwelder, 1992). It is difficult to ascertain the origin of ancient lime muds due to diagenesis. Pervasive dolomitization of the Sinnipee

Group carbonate obliterated even the geochemical traces. It is only speculated that most of the Platteville lime muds were originated from direct precipitation and disintegration of calcareous algae whereas considerable amount of the Galena muds were originated from breakdown of bioclasts.

Whatever origin the mudstone lithofacies has, it is interpreted to have deposited relatively quiet environment based on the thickly accumulated fine-grained sediments, scarceness of current structures and intercalating grainstone beds indicating high energy. Such environments exist in deep subtidal well below FWB in an open marine or in a protected area partly or completely closed by barriers. The fauna indicates open marine precluding the interpretation of completely closed protected environment although the faunal diversity and abundance are lower than those in the other lithofacies. Therefore, protected environments with open circulation is postulated for the deposition of the mudstone lithofacies in the Platteville Formation. However, the Type 3 mudstone lithofacies is interpreted to have been deposited in an open marine mid- to outer ramp environments based on the fauna and the associated abundant storm beds.

7. NODULAR CARBONATE (NC)

Description

The nodular carbonate lithofacies is a very fine crystalline limestone/dolostone intercalated with thin irregular argillaceous seams. This lithofacies comprises most of the Mifflin Member except

uppermost beds. It is characterized by nodular or ribbon-like appearance due to concentration of argillaceous material as 0.3-1 cm-thick irregular layers (Figs. 12A, 40 - 43). The clay content appears approximately 10-31%. This lithofacies consists of alternation of two lithologies: carbonate and argillaceous.

The carbonate lithology is 0.5-3 cm-thick forms laterally continuous to discontinuous mudstone to bioclastic wackestone beds, light-gray to yellowish-gray in color. Beds are often nodular when it is surrounded by the argillaceous lithology (Fig. 41). The nodules are elliptical and elongated laterally, 0.5-2 cm in height and 1-5 cm in width. The argillaceous lithology is greenish- to bluish-gray in color. Its thickness varies ranging from approximately laterally continuous layers up to 1 cm thick to discontinuous thin seams around nodules. The boundaries between the carbonate and the argillaceous lithologies are generally gradational and marked by anastomosing swarms of fine clay seams and microstylolites. However, the upper boundaries of the nodules are usually very sharp and marked by stylolites while the lateral boundaries are gradational and show diffuse boundary (Fig. 42).

This lithofacies is moderately to strongly bioturbated by 2-4 mm-wide *Chondrites* burrows. The burrows are circular to elliptical in the carbonate lithology, but they are more compressed and elongated laterally in the argillaceous lithology. In some beds, only the argillaceous lithologies are highly bioturbated whereas the carbonate lithologies are not bioturbated (Fig. 43). In those un-bioturbated beds, the nodules are irregular in shape and lack bioclasts within them. This lithofacies contains normal marine fauna such as brachiopods, crinoids,



Fig. 40. Field photograph of the lithofacies NC. The darker layers or partings are argillaceous. The lighter layers and nodules are carbonate lithology. Note abundant *Chondrites* burrows and a ferruginous hardground below. 2.5 cm-wide coin for scale. Mifflin Member. Beaver Dam Qr., Locality 5.

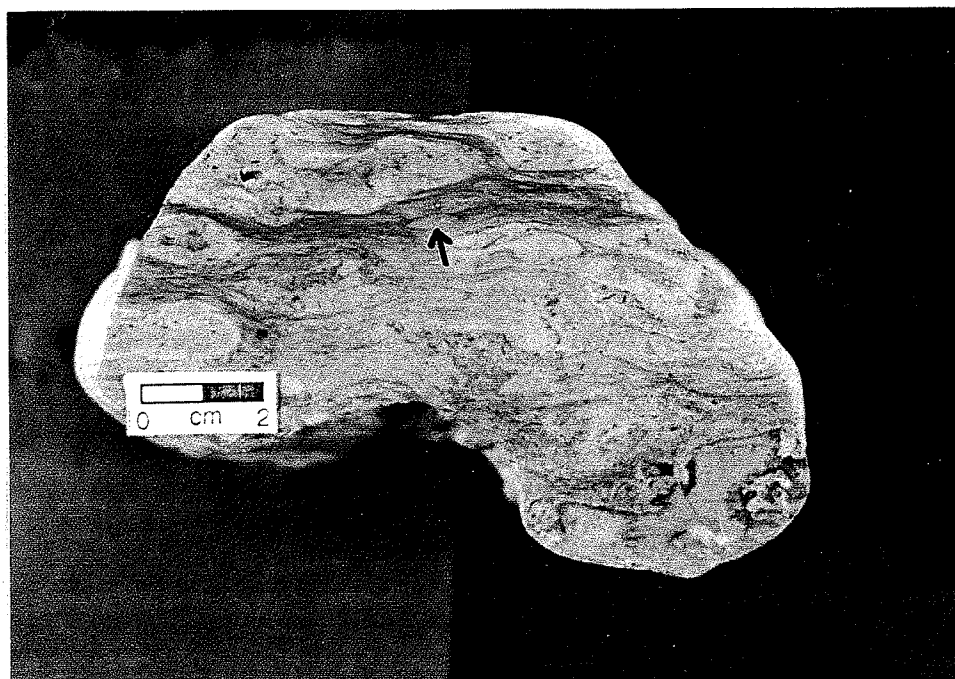


Fig. 41. Rock slab photograph of the lithofacies NC showing carbonate nodules surrounded by argillaceous lithology. Note the compressed burrows in the argillaceous lithology (arrow). Mifflin Member. Beaver Dam Qr., Locality 5 [U.W.1896/8].

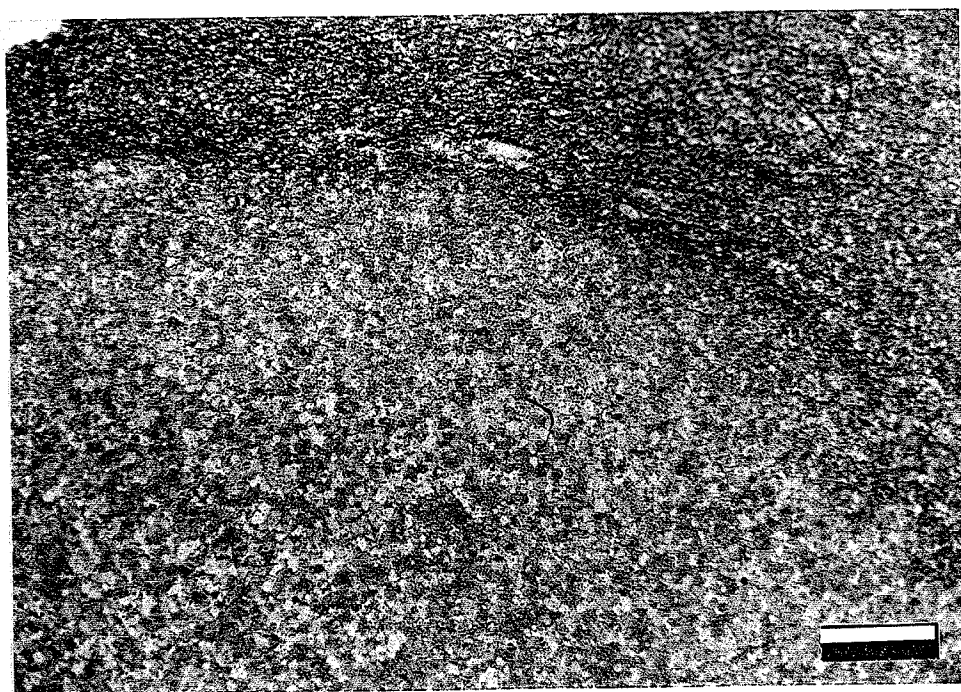


Fig. 42. Photomicrograph of a nodule in the lithofacies NC. The upper boundary of the nodule is relatively sharp while the lateral boundary is diffuse. The scale bar is 1 mm long. PPL. Mifflin Member. Beaver Dam Qr., Locality 5 [U.W.1986/19].

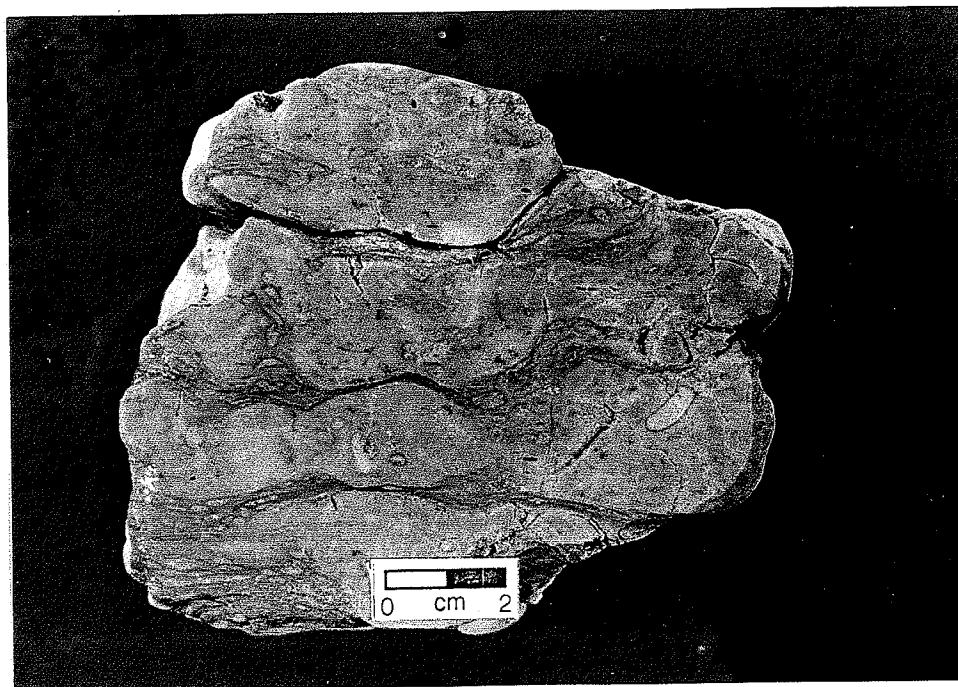


Fig. 43. Rock slab photograph of the lithofacies NC. Note the irregular nodule shape and restricted occurrence of Chondrites burrows to the argillaceous lithology. Mifflin Member. Sun Prairie Qr., Locality 17 [U.W.1896/9].

bryozoans, and gastropods. This lithofacies is associated with thin-bedded intraclastic/bioclastic grainstone. The intercalating grainstone beds are particularly abundant in the upper part of this lithofacies (Figs. 6, 7). Ferruginous hardgrounds often occur in this lithofacies on top of the carbonate lithology.

Interpretation

Nodular limestone/dolostone is a descriptive term that encompasses all kinds of carbonate rock having 'nodular' structures. There is no single mechanism nor sequence of mechanisms that can explain the origin of all kinds of nodular carbonates. Therefore, each case must be considered individually. The genesis of nodular limestones has been attributed to: (1) sedimentary boudinage (McCrossan, 1958), (2) early diagenetic concretionary precipitations (Jenkyns, 1974), (3) burrowing (Abed and Schneider, 1980), and (4) late burial diagenesis (Garrison and Kennedy, 1977). The suggested depositional environments for nodular limestones range from peritidal (Abed and Schneider, 1980) to deep slope (Mullins et al., 1980).

The nodular carbonate of the Platteville Formation is interpreted to have deposited in a subtidal environment below FWB above SWB. This interpretation is based on the criteria of lack of physical structures indicating shallow-water or intertidal environment; there are no mud cracks, cross beddings, or ripples in this lithofacies. The abundance of the associated intraclastic/bioclastic lithofacies indicates storm influence above SWB.

Judging from the diffuse and gradational nature of the

argillaceous seams and the more compressed burrows within them (Fig. 41), the argillaceous seams are formed by pressure solution due to compaction during burial (i.e., Wanless, 1979). However, the following evidences suggest that some of the limestone nodules were formed early and led to differential compaction in later burial diagenesis: (1) the boundaries are sharp at the top and bottom of the nodules while diffuse and gradational at the sides (Fig. 42) indicating more concentration of stress along the upper and lower boundaries of the nodules than the sides, which imply the pre-existence of harder substances during compaction; (2) some nodules lack burrows while surrounding argillaceous seams have abundant compressed burrows (Fig. 43), which implies that the nodules have grown before bioturbation or early cementation occur around nucleus pushing out pre-existing sediments. Möller and Kvingan (1988) suggested early formation of limestone nodules in a similar depositional setting.

Four stages are defined for the origin of the nodular structures of this lithofacies.

(1) sedimentation of lime mud and clay in a quite subtidal environment

The precursor sediments of the nodular carbonate could be either alternation of pure lime mud and clay or homogeneous argillaceous sediments. However, considering the fairly good lateral continuity of the argillaceous/carbonate layers in most horizons and the diffuse boundary between the two lithologies, the original sediments were probably alternation of varying degree of argillaceous sediments and lime mud.

(2) pervasive bioturbation by *Chondrites* burrows

(3) early micritic cementation of limestone locally depending on the chemistry of microenvironments and probably nucleus

Most space (70-80%) of lime mud sediments is occupied by water before compaction. Thus, if cementation occur impartially in the small microenvironments, burrows are preserved inside nodules. If cementation occur around nucleus, nodules grow within argillaceous sediments pushing out the surrounding sediments.

(4) burial compaction resulting in differential pressure solution between nodules

The late diagenesis at the last stage may have produced many of the nodular beddings as well as modification of the early formed nodules. In conclusion, the nodular structures of the nodular carbonate lithofacies of the Platteville Formation have been produced by more than one process - depositional heterogeneity, early cementation and later modification or enhancement by burial diagenesis. However what caused the differential early cementation is still a question.

8. THIN-BEDDED GRAINSTONE (TBG)

Description

This lithofacies consists of coarse sand- to pebble-grain size intraclasts and sand-grain size bioclasts. It is characterized by grain-supported texture, sharp and commonly erosional lower boundary, gradational upper boundary, and normal grading. It is medium gray to greenish-gray in color depending on the clay content. Most beds are

TYPES	TYPE 1	TYPE 2	TYPE 3
OCCURRENCE	Mifflin Member	Ion sub-member	upper Dunleith sub-member - Wise Lake Member
APPROXIMATE % OF INTRACLASTS	0-70%	< 1%	<1%
INTRACLAST TYPES	Mostly Type A with occasional Type B.	Type A	Type A
BIOCLAST TYPES	Type A > Type B	Type A > Type B	Type A < Type B
RELATIVE PROPORTION OF COMPONENT GRAINS			
Autochthonous vs. Allochthonous Components.	Auto- (Bio-B, Intra-A,B) \approx Allo- (Bio-A)	Auto- (Bio-B, Intra-A) < Allo- (Bio-A)	Auto- (Bio-B, Intra-A) \gg Allo- (Bio-A).
INTERPRETATION (Relative Proximity to Paleo-shoal)	Proximal to intermediate.	Proximal	Distal

Bio-A: Type A bioclast; Intra-A: Type A intraclast; Auto-: Autochthonous; Allo-: Allochthonous; \approx : Approximately equals to.

Table 8. Relative proportion of grains in the thin-bedded grainstone lithofacies in the Sinnipee Group and interpreted proximity to the paleo-shoal. The interpretation is based on relative proportion autochthonous vs. allochthonous components.

thin-bedded and maintain constant thickness laterally at outcrop scale, but some thicken and thin, or laterally pinch out. The distinction between grainstone and packstone is very difficult to make except few occasions because of pervasive dolomitization.

This lithofacies occurs in three stratigraphic intervals: Mifflin Member (Type 1), Ion sub-member (Type 2), and upper Dunleith sub-member to Wise Lake Member (Type 3). They differ from each other with constituents, grain size, and associated lithofacies. Table 8 summarizes and interprets the component grains and their relative proportion in each type of TBG lithofacies in Sinnipee Group.

Type 1 is characterized by high intraclast content. The proportion of intraclasts varies from 0 to 70% and generally increases to the south. With decreasing content of intraclasts it changes into bioclastic grainstone with or without minor intraclasts sparsely floating in the bioclastic grainstone matrix. The floating intraclasts are usually black due to pyrite staining, often have 2 mm-wide borings, and reach up to 10 cm in length. This lithofacies is weakly to moderately bioturbated by 2-5 mm-wide *Chondrites* burrows. Most intraclastic grainstones are poorly sorted and poorly graded (Fig. 44a). The bed thickness ranges from 1 cm to 8 cm but they reach up to 15 cm in amalgamated beds (Fig. 44a).

The intraclasts of Type 1 thin-bedded grainstone are mostly Type A intraclasts with occasional Type B intraclasts (Table 8). Most intraclasts are platy and discoidal in shape but some are near spherical (Fig. 44b). Most of them show good roundness but intraclasts with sharp edge in irregular shape are not uncommon (Fig. 44a). The size of

intraclasts ranges from few millimeters to 7 cm in length. Most of them are dark gray with fully disseminated pyrite and some are dark gray only at the edge (Fig. 44b). The intraclasts consist of fossiliferous mudstone to wackestone with lesser grainstone or laminated calcisiltite (Fig. 45). In general, intraclasts of pure mudstone are more spherical (Fig. 44b). The grains of the grainstone intraclasts consist of bioclasts and/or mm-sized intraclasts. The lamination of the laminated calcisiltite intraclasts consists of alternation of argillaceous laminae with disseminated very fine-crystalline dolomite and carbonate laminae composed of coarser crystalline-dolomite. The orientation of the lamination always coincides with the long axis of the pebble (Fig. 45a).

The texture and composition of the intraclasts in the Type 1 TBG lithofacies are commonly related with the underlying lithologies. In general, the intraclasts are more common above ferruginous hardgrounds. Occasionally the intraclastic grainstone beds overlie nodular carbonate having mudstone nodules surrounded by thick shaly layers, then the grainstone beds often show gradational boundary and contain mudstone intraclasts with near spherical shape (Fig. 44b). The same is true in the other cases (Fig. 45). Where the intraclasts are in contact, the boundaries are sutured (Fig. 46).

The matrix of the Type 1 TBG lithofacies consists of well-sorted bioclasts, smaller size intraclasts, and lime mud. Most bioclasts are coarse sand-sized but some brachiopod fragments reach up to 1 cm in maximum size. In general, there are more Type A and less Type B bioclasts. Most bioclasts are fragmented, dark gray, almost all are

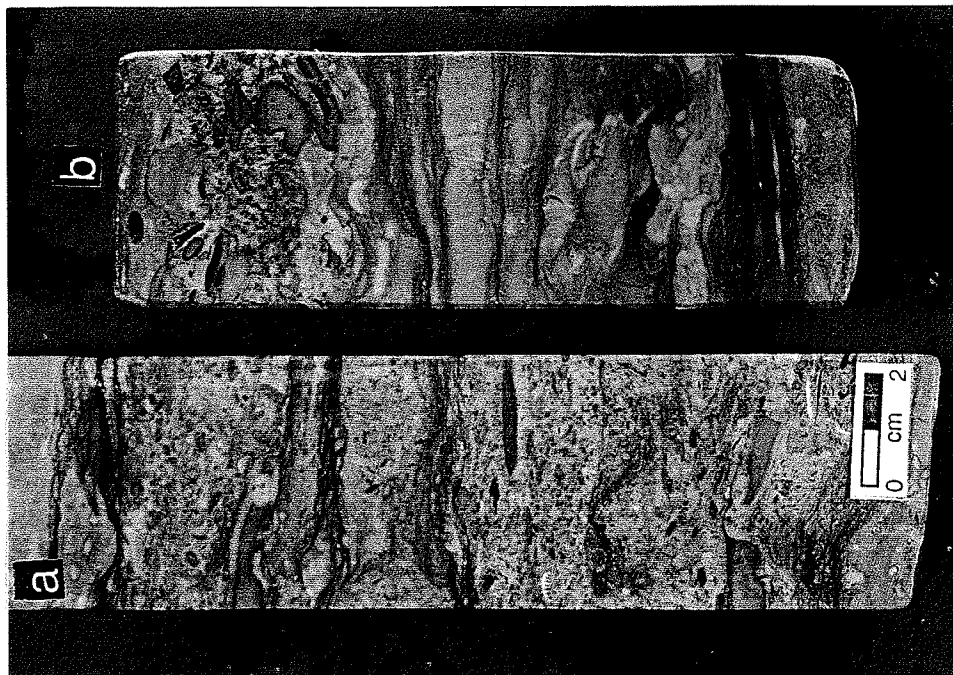


Fig. 44. Core slab photograph of intraclastic grainstone (Type 1 TBG). a: Amalgamated beds. Note poor sorting and platy shape of most intraclasts. Mifflin Member. Locality RA. WGNHS Sample Repository BD318, 570'. b: Irregular but spherical shape of intraclasts with pyrite staining at the edge. Mifflin Member, Locality JE. WGNHS Sample Repository BD323, 287'.

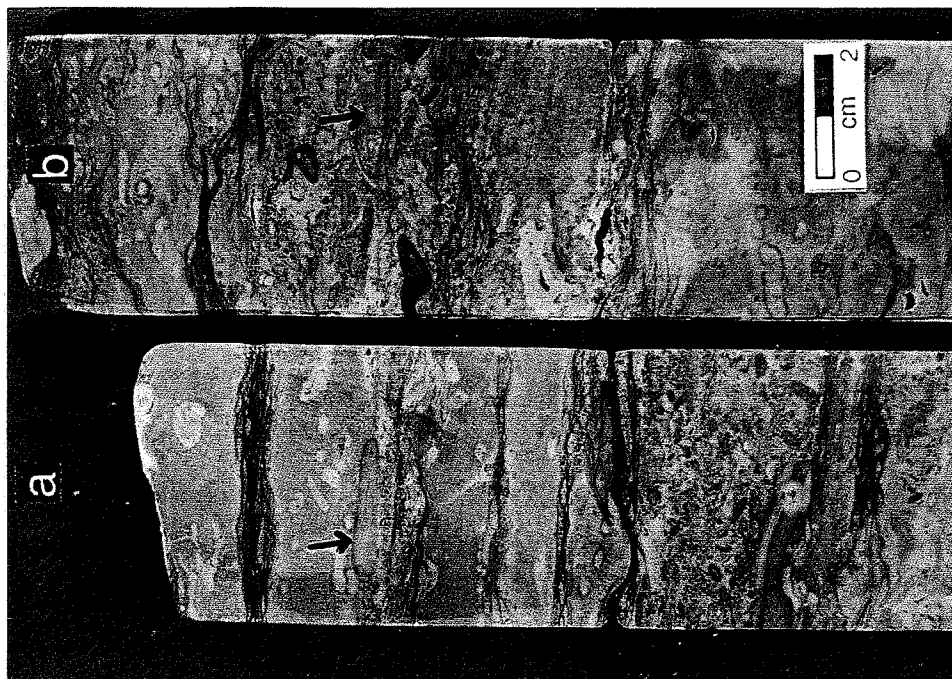


Fig. 45. Core slab photograph showing the relationship between the intraclasts and the underlying lithologies. a: Laminated intraclast (arrow) above laminated bed. Mifflin Member. Locality RA. WGNHS Sample Repository BD318, 570'. b: Bioclastic grainstone intraclasts (arrow) above bioclastic grainstone. Mifflin Member. Locality WK-2. WGNHS Sample Repository BD320, 341'.

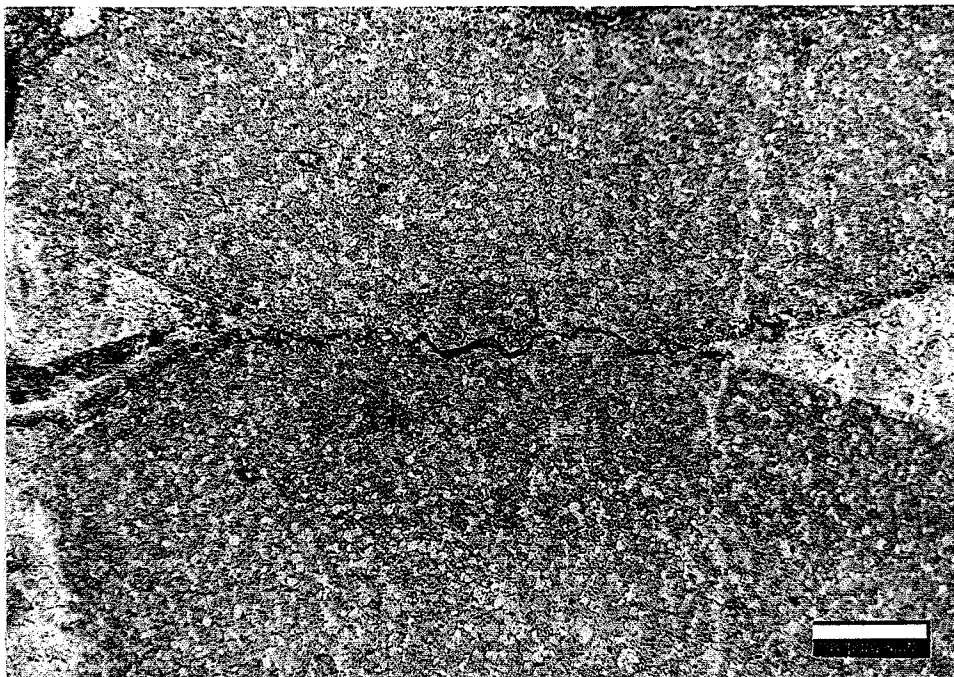


Fig. 46. Photomicrograph of intraclastic grainstone lithofacies (Type 1 TBG) showing sutured boundary between mudstone intraclasts. Scale bar is 1 mm long. PPL. Same sample as 44b. Mifflin Member. Locality JE [U.W.1896/20].



Fig. 47. Photomicrograph of Type 1 TBG lithofacies showing matrix consisting of skeletal fragments. Most of them are Type A bioclasts. Note good sorting and fragmentation of the bioclasts. Scale bar is 1 mm long. PPL. Same sample as 44b. Mifflin Member. Locality JE [U.W.1896/20].

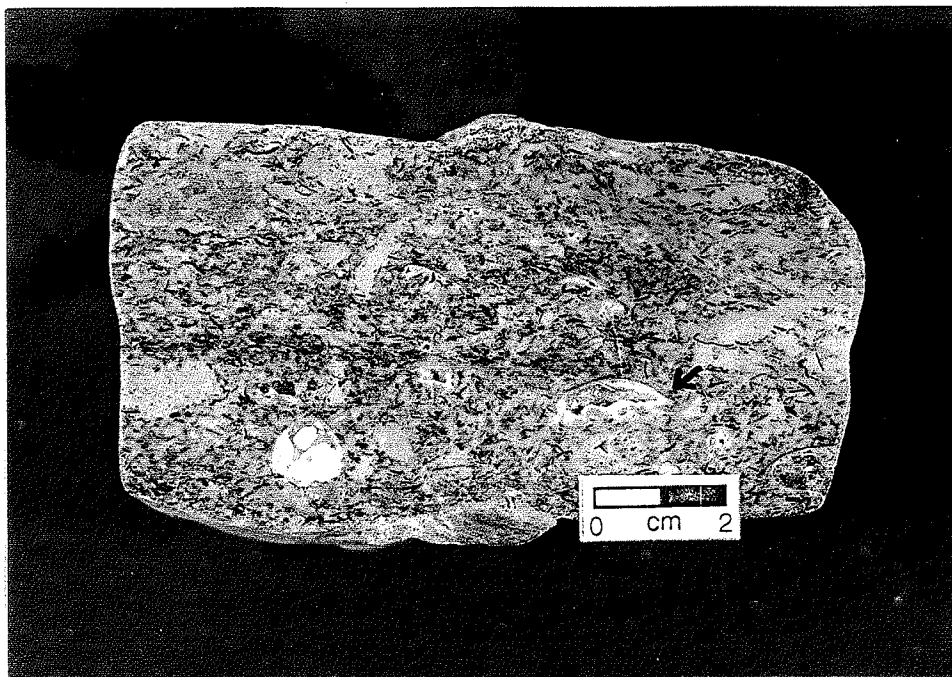


Fig. 48. Rock slab photograph of bioclastic grainstone (Type 2 TBG) consisting of pyrite-stained bioclasts and floating intraclasts. Burrows are filled with green clay. Note the shelter porosity below a brachiopod shell (arrow). Ion sub-member. Watertown Qr., Locality 2 [U.W. 1896/10].

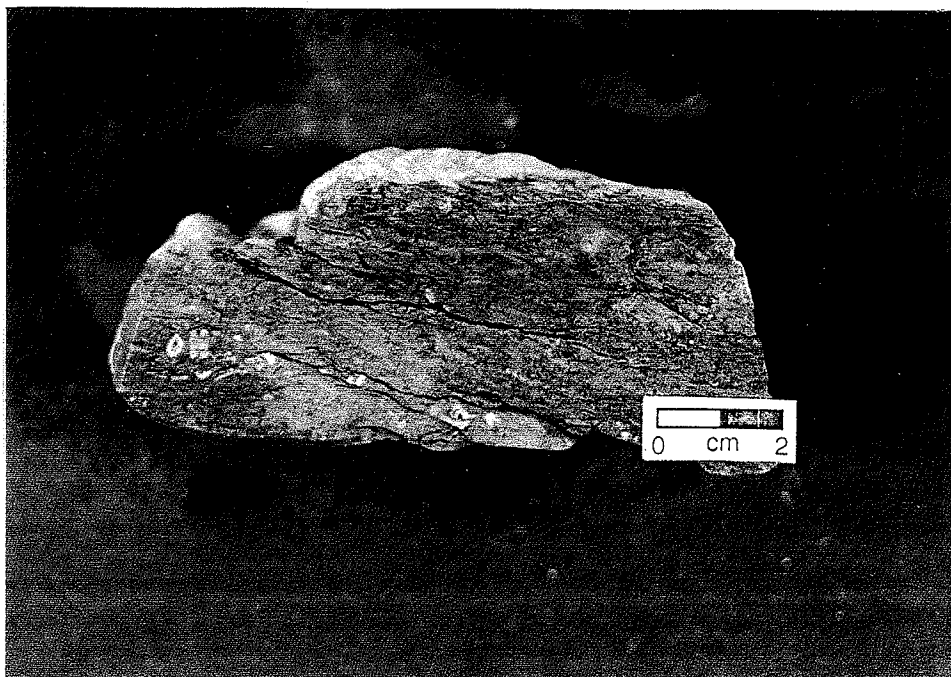


Fig. 49. Rock slab photograph of shaly bioclastic packstone. Note the local concentration of bioclasts, which are probably remnants of the former grainstone bed. Ion sub-member. Watertown Qr., Locality 2 [U.W. 1896/11].

disarticulated, although the degree of abrasion is not clear due to dolomitization (Fig. 47). The Type A bioclasts are all stained by pyrite while about half of the Type B bioclasts are stained by pyrite in this lithofacies. The fauna is brachiopods, crinoids, bryozoans, and trilobites in order of abundance.

The Type 2 TBG lithofacies differs from the Type 1 in that it is thicker-bedded, it is commonly associated with shale lithofacies, and intraclasts are rare (Table 8). It is occasionally parallel-laminated, or cross-stratified in rare occasion. The cross stratification plunges to the south with approximately 20°, which was measured in a horizontal bed. Moldic to shelter porosities are common in the grainstone beds (Fig. 48). This lithofacies is usually moderately to strongly bioturbated by 0.3-1 cm-wide burrows. Most burrows are extended from the shale laminae above to grainstone below and are filled with green clay (Fig. 31). Pervasive bioturbation often results in complete mixing of bioclasts and the clay, and the skeletal grainstone becomes an argillaceous skeletal packstone (Fig. 49). The bioclasts comprising this lithofacies are mostly Type A with minor Type B; they are very well sorted, highly fragmented and pyrite-stained, and ranges in size from 0.2 mm to 20 mm. The fauna includes brachiopods, bryozoans, crinoids, and trilobites. The common pyrite staining in the bioclasts makes the identification of them easy despite dolomitization (Fig. 50). Terrigenous silt is common and particularly abundant up to 10% in some clay-rich packstone beds (Fig. 51). The terrigenous silt is subangular to subrounded, mostly quartz grains with minor feldspar including microcline and plagioclase. The proportion of the feldspar silt is



Fig. 50. Photomicrograph of bioclastic grainstone (Type 2 TBG). Most bioclasts are stained by pyrite and identified only by morphology. Scale bar is 1 mm long. This photo is taken by inserting a white card below thin section. Ion sub-member. Locality WK-1 [U.W.1896/21].

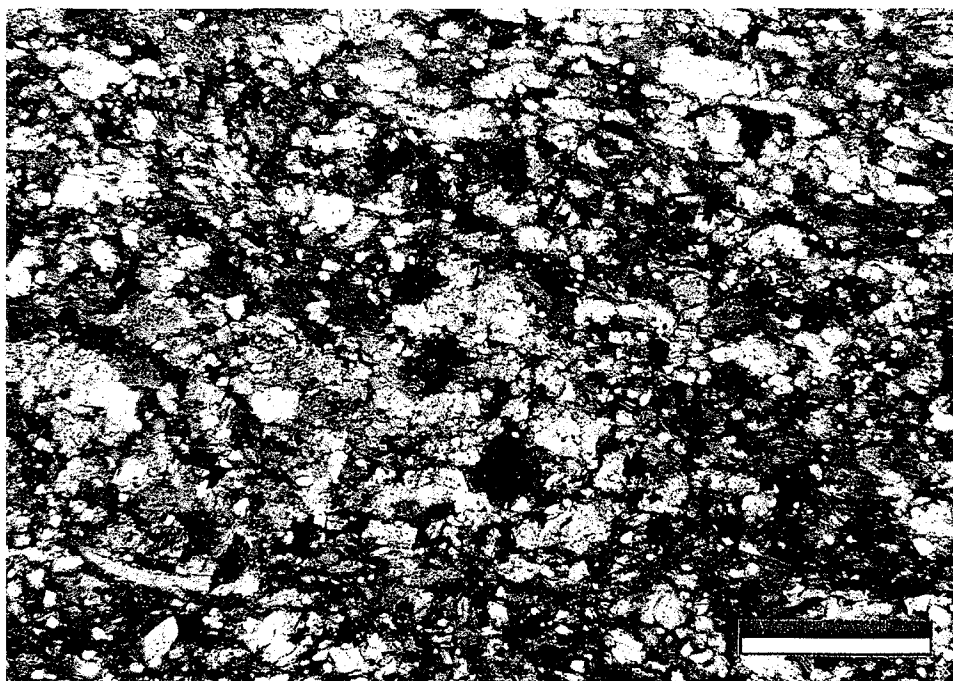


Fig. 51. Photomicrograph of the argillaceous bioclastic packstone (Type 2 TBG) showing abundant terrigenous silts. The larger crystals are dolomite crystals. Scale bar is 0.5 mm long. XPL (crossed polars). Ion sub-member. Locality WK-1 [U.W.1896/21].

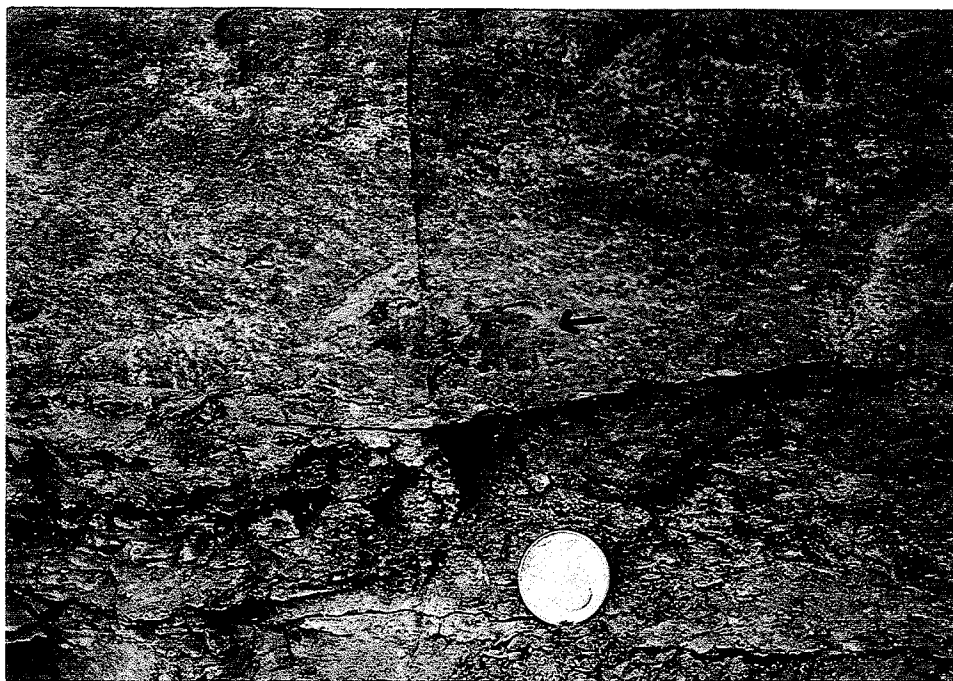


Fig. 52. Field photograph of the bioclastic grainstone (Type 2 TBG) containing bored intraclasts. Note that the borings exist both on the upper and lower sides of the intraclast (arrow). Coin for scale is 2.5 cm in diameter. Ion sub-member. Watertown Qr., Locality 2.

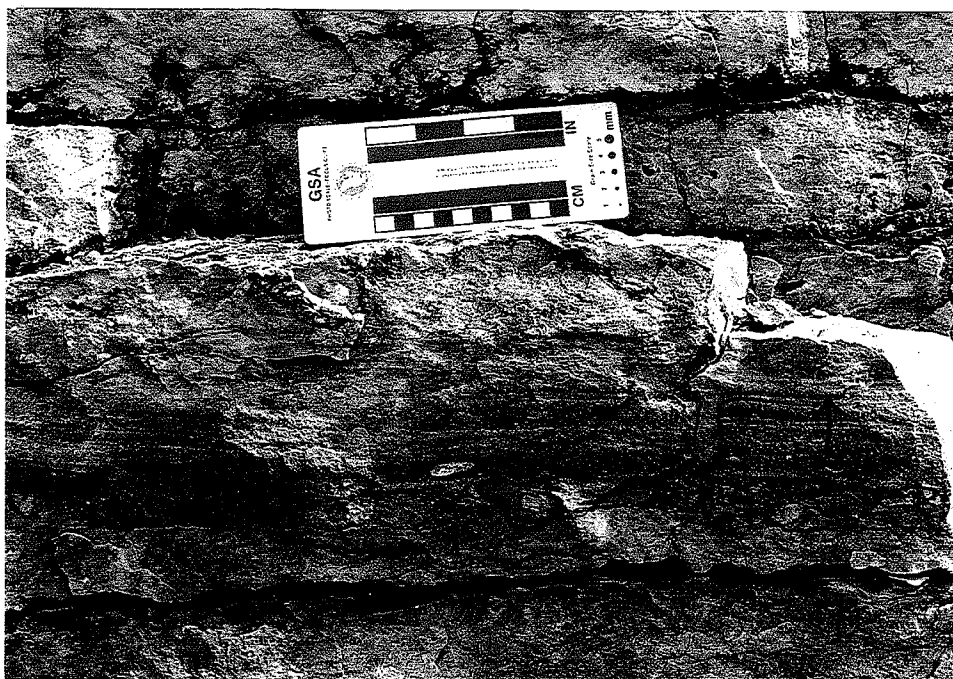


Fig. 53. Field photograph of Type 3 TBG lithofacies showing low-angle cross lamination (hummocky cross stratification?). Note also the dark gray stained hardground below the grainstone bed. Wise Lake Member. Waupun Qr., Locality 9.

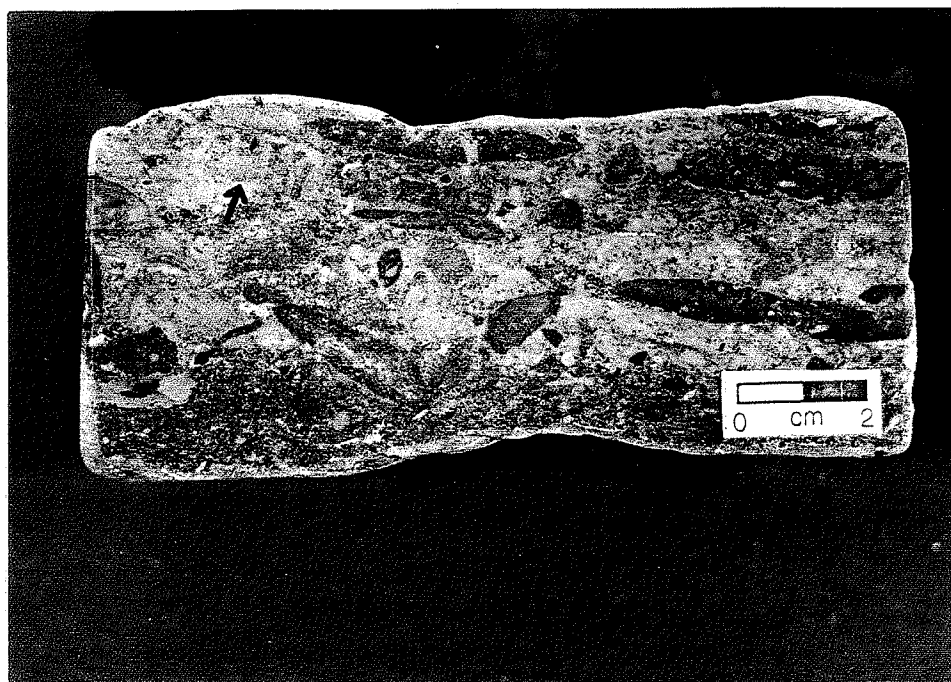


Fig. 54. Rock slab photograph of Type 3 TBG lithofacies. Most of the intraclasts are platy in shape and pyrite-stained and bored. The skeletal fragment at upper left hand corner (arrow) is Receptaculites. Upper Dunleith sub-member. Rosandale Qr., Locality 16 [U.W. 1896/12].

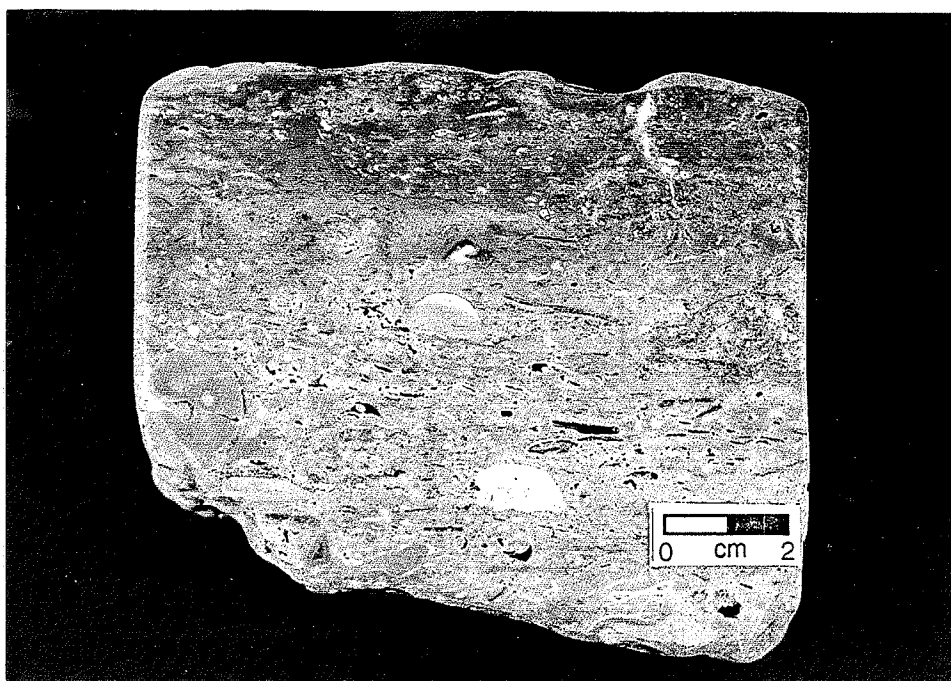


Fig. 55. Rock slab photograph of typical Type 3 TBG lithofacies. The bioclasts are poorly sorted and retain original shape. Note abundant shelter and moldic porosities some of which are filled with white silica cement. Wise Lake Member. Waupun Qr., Locality 9 [U.W. 1896/13].

approximately 10-20%. Dark gray to black intraclastic pebbles occur sparsely in some grainstone beds. They usually have 2-3 mm-wide borings (Fig. 52).

The thin-bedded grainstone lithofacies (Type 3) occur widely throughout the middle to upper Galena Formation as intercalating thin beds in fossiliferous mudstone, skeletal wackestone to packstone, and porous dolostone lithofacies. It ranges from 1 cm to 10 cm in bed thickness. Recognition of this lithofacies is difficult particularly when it occurs in intervals of pure carbonate and does not show any difference in dolomite crystal size from the lithologies above and below. Some grainstone beds are parallel- or low angle cross-laminated (Fig. 53). This lithofacies consists mostly of bioclasts with rare dark gray to black bored intraclasts but in some beds the intraclasts occur in great abundance (Fig. 54). The bioclasts are mostly Type B and rare Type A: unabraded and articulated (Fig. 55), although they may be fragmented and disarticulated in well sorted and laminated grainstone beds. The fauna includes brachiopods, crinoids, gastropods, bryozoans, trilobites, and cephalopods in order of abundance.

Interpretation

The thin-bedded grainstone lithofacies is interpreted as storm tempestites deposited in a middle ramp below FWB and above SWB. This interpretation is based on the following characteristics:

- (1) The bases of the thin-bedded grainstone do not show any channel morphology, although they are commonly erosive
- (2) The beds are widely correlated over several 10's of km's

despite the thin bed thickness, although they commonly pinch and swell laterally at m-scale

- (3) They commonly show parallel-lamination, occasionally show low angle cross lamination (hummocky cross-stratification?), and sometimes are normally graded
- (4) Associated lithofacies are interpreted as mid- to deep ramp deposits.

Similar thin-bedded skeletal/intraclastic grainstones have been reported and interpreted as storm deposits (Jones and Dixon, 1976; Kreisa, 1981; Kreisa and Bambach, 1982; Sepkoski, 1982; Byers, 1983; Aigner, 1985; Brookfield and Brett, 1988). Periodic storms produce intense bottom-shear conditions well below FWB during storm peak and offshore-directed gradient currents (Kreisa, 1981; Aigner, 1985). The thin-bedded grainstone lithofacies was probably generated by in-situ erosion and redeposition of sediments and/or was introduced as suspension load with occasional bedload transport from the inner ramp of skeletal shoals.

Intraclastic grainstone (flat-pebble conglomerate) has been reported by several workers as intertidal deposits (Braun and Friedman, 1969; Larporte, 1969; Wilson, 1975), reef slope deposits (Enos and Moore, 1983), and basin margin deposits (Cook and Mullins, 1983). Modern analogues also have been reported from supratidal flats (Roehl, 1967; Shinn, 1968). The intraclastic grainstone lithofacies in the Platteville Formation (Type 1), however, is interpreted to have deposited in different environments and/or process. Considering the associated nodular carbonate lithofacies, the intertidal to supratidal

setting is excluded from the probable depositional environment for the intraclastic grainstone because the associated lithofacies do not show any characteristics indicative of this environment such as fenestral structures, mud cracks, and tidal bedding. Furthermore, there are no intraclasts of microbial laminite contrary to what would be expected if they were derived from supratidal flats. The basin margin and reef slope depositional setting is also excluded because units are thin, less than 10 cm, clasts are small and do not consist of reef-forming organisms, and the matrix does not consist of shale or reef-derived bioclasts.

The thin-bedded intraclastic/bioclastic grainstone (Type 1) resemble that described by Jones and Dixon (1976) in following characteristics: good roundness and flat shape of intraclasts in varying proportion within a bioclastic matrix rich in crinoids, brachiopods, and trilobites. They suggested that during short-lived phases of high-energy conditions some of the unconsolidated sediments were ripped-up and broken and the resulting debris accumulated as thin units of intraformational conglomerate, intraclastic shelly limestone, and shelly limestone. They also suggested that the lower proportion of intraclasts in the intraclastic shelly limestone probably indicated a slightly lower energy regime than for the intraformational conglomerate. The relative proportion of intraclasts in the thin-bedded grainstone in the Sinnipee Group, however, seems more related with relative availability of intraclasts and bioclasts than the intensity of hydraulic energy regime alone.

Most intraclasts seems to have derived from the underlying beds

or at least not far from the depositional site, considering the close relationship of the intraclast shape and composition with the underlying lithologies. The Type A intraclasts are interpreted to have derived from the ferruginous hardgrounds considering the higher occurrence of these intraclasts above the hardgrounds. The Type B intraclasts were probably derived from the early formed nodules of the nodular carbonate lithofacies some of which were possibly exposed to sediment-water interface before final erosion enabling pyrite-staining. This interpretation is also supported by the close resemblance between those intraclasts and the nodules of the nodular carbonate lithofacies below (Fig. 44b).

The type A bioclasts in Type 1 TBG are interpreted to have derived from skeletal shoals, which might have existed landward from the depositional site based on the good sorting and taphonomic characteristics of the bioclasts. The taphonomic criteria also suggest that Type B bioclasts are deposited rapidly by episodic high energy (Brett and Baird, 1986).

Therefore, the sediments of Type 1 TBG lithofacies are interpreted to be a mixture of shoal-derived bioclasts (Type A) and in-situ derived intraclasts and bioclasts (Type B). This interpretation also explains general northward (toward paleo-shoal) increase of the bioclast proportion in this lithofacies.

The thin-bedded grainstone lithofacies in the lowermost Galena Formation (Type 2) is also interpreted as a storm deposit but with a closer proximity to the source area than Type 1. The followings are evidence for the interpretation:

- (1) Bed thickness is greater than type 1; some laminated bioclastic grainstone beds reach up to 15 cm in thickness
- (2) Laminated grainstone beds are more abundant which indicate higher energy
- (3) Some beds are cross-stratified which indicate bottom traction current in nearshore
- (4) The size of the bioclasts are generally larger than the size of those in the Type 1
- (5) Many grainstone beds are amalgamated with thin intervening shale partings.

The relative proportion of the component grains also supports the above interpretation. Therefore, this lithofacies probably deposited just below FWB by continuous wave erosion and transportation of shoal deposits by storm reworking.

Most of the thin-bedded grainstone lithofacies (Type 3 TBG) in the middle to upper Galena probably deposited without much input of bioclasts from the skeletal shoals except the laminated grainstone beds. This inference is based on the fact that the comprising bioclasts are mostly Type B (Table 8) and that most beds are less than 5 cm in thickness and rarely amalgamated. The associated lithofacies (skeletal wackestone to packstone or mudstone) also support the above interpretation.

9. POROUS DOLOSTONE (PD)

Description

This lithofacies is a fine- to medium-crystalline dolostone. It is common in Nachusa Member, upper Dunleith sub-member, and Wise Lake Member, south of Dodge County. This lithofacies is 10's m thick and is characterized by irregularly distributed vesicular pores and vuggy porosity (Fig. 56). The original depositional texture of this lithofacies probably corresponds to fossiliferous mudstone to packstone with occasionally intercalating thin-bedded grainstone. It is light brown to buff in color and medium-bedded with very thin argillaceous partings. Terrigenous silt occurs throughout this lithofacies in minor (1%) proportions. Stylolites are common containing phosphate grains, clay, and pyrite (Fig. 57). Hardgrounds are common to abundant in this lithofacies, one in every 5-20 cm interval. There is a complete spectrum of the hardgrounds with prominence. Some hardgrounds are vague and are not easily distinguished from stylolites or argillaceous partings. Chert nodules are locally abundant. The size of the nodules ranges from 1 cm to 6 cm in height and elongated laterally. The color of the nodules is mostly white with occasional dark purplish-gray. This lithofacies is moderately to strongly bioturbated by 1-2 cm-wide *Thalassinoides* burrows (Fig. 58). The boundaries of the burrows are diffused except when they are stained by pyrite on hardgrounds. Fauna in this lithofacies consists of molds of bryozoans, brachiopods, gastropods, and trilobites. The most peculiar of them is bryozoan molds. The bryozoan molds occur abundantly throughout this lithofacies



Fig. 56. Field photograph of porous dolostone lithofacies showing irregularly distributed vesicular pores and vuggy porosity. Coin for scale is 2.5 cm in diameter. upper Dunleith sub-member. Fort Atkinson Qr., Locality 1.

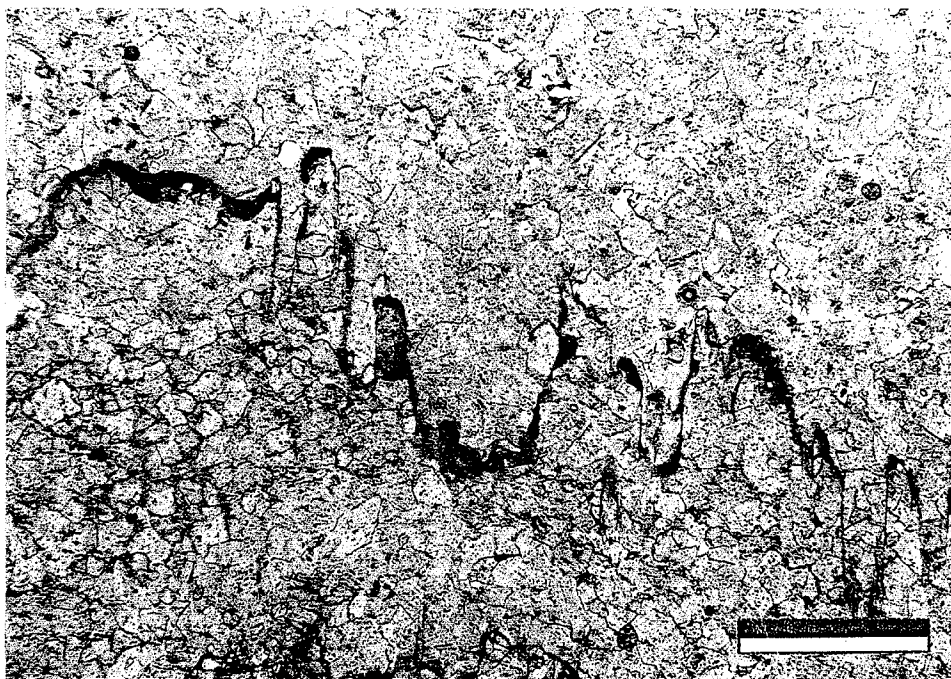


Fig. 57. Photomicrograph of porous dolostone lithofacies showing a stylolite rich in phosphate grains and pyrite. The phosphate grains are compacted losing their identity as grains. Scale bar is 0.5 mm long. PPL. Uppermost upper Dunleith sub-member. Locality WK-1 [U.W.1896/22].

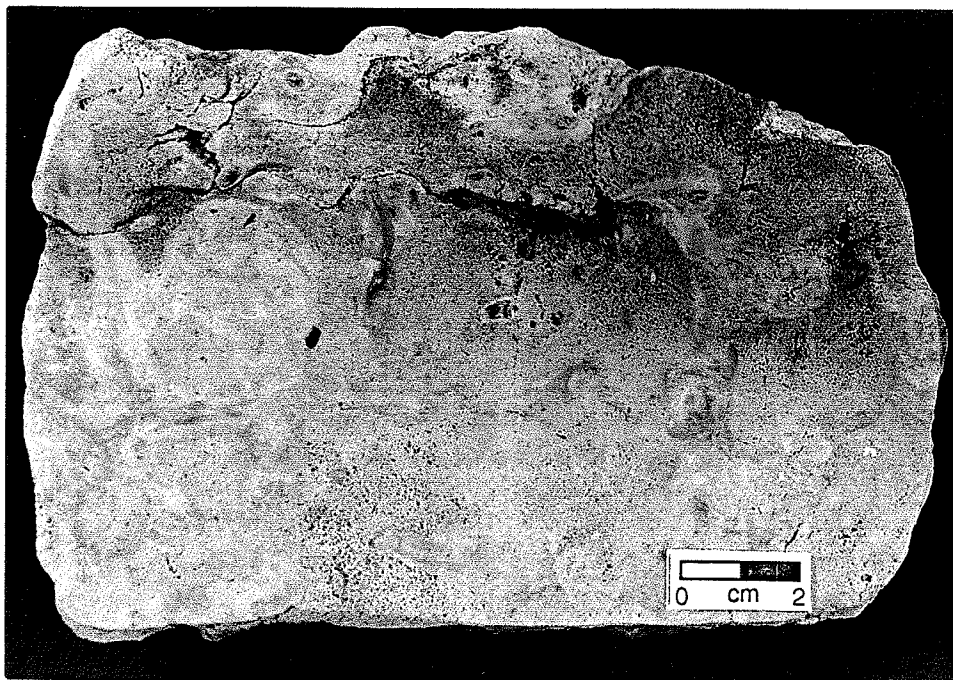
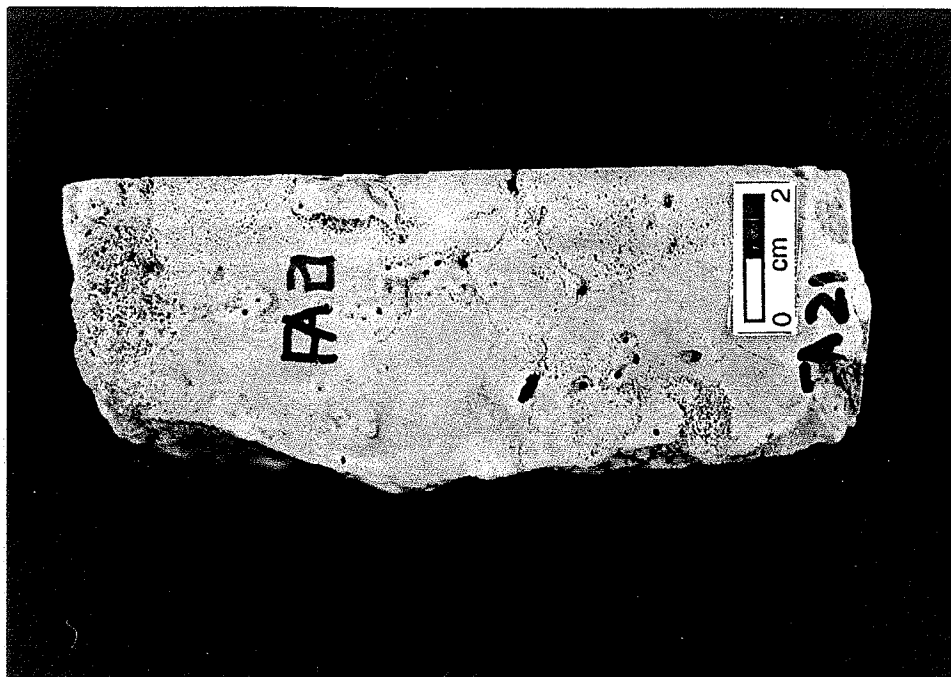


Fig. 58. Rock slab photograph of porous dolostone lithofacies showing irregularly distributed vesicular pores. Considering the shape and scale, they are probably *Thalassinoides* burrows composed of coarse-crystalline dolomite. Note the ferruginous hardground (reddish brown) associated with the *Thalassinoides* burrows. upper Dunleith sub-member. Fort Atkinson Qr., Locality 1 [U.W. 1896/14].



Fig. 59. Core sample taken from the upper Dunleith sub-member, locality WK-2 showing tube-like bryozoan molds. WGNHS Sample Repository BD320, 306'.

A.



B.



Fig. 60. Rock slab photographs showing bryozoan molds. Up to the left. upper Dunleith sub-member. Fort Atkinson Qr., Locality 1 [U.W. 1896/15]. A: Tube-like bryozoan molds consisting of 1-2 mm-wide hollows and/or linings composed of fine-crystalline dolomite. B: Another side of the same sample as A. The molds appear burrows, but in fact they are bryozoans.

as 3-8 mm-wide cylinders and/or tubes composed of fine crystalline dolomite (Fig. 59). The tubes are composed of 1-2 mm thick linings and 1-1.5 mm-wide hollows (Fig. 60A). The molds often appear as irregular burrows filled with finer materials (Fig. 60B). However close investigation suggests that they are bryozoans molds produced by partly or whole dissolution of bryozoans.

Interpretation

This lithofacies is inferred to be a dolomitized equivalent of fossiliferous mudstone to packstone with occasional thin (up to 2 cm thick) bioclastic grainstone lenses if the cm-thick vesicular lenses/beds are molds of bioclasts in grainstone to packstone beds. This interpretation is also supported by the presence of abundant bryozoans and by the observation that this lithofacies to the north correlates to the skeletal wackestone to packstone lithofacies with intercalating grainstone (Appendix C). Considering their shape and size of the irregularly distributed vesicular porosity zones (Fig. 58), they are probably *Thalassinoides* burrows. The coarser crystal size of the burrows is inferred to be caused by superimposed dolomitization. Selective weathering of coarse crystalline dolomite seems to result in vesicular porosity in the burrows. Therefore, based on the inferred texture and contained open marine fauna, this lithofacies is interpreted to have deposited in a mid-ramp.

10. CRINOIDAL WACKESTONE (CW)

Description

This lithofacies occur in the uppermost Galena Formation. Its thickness ranges from 2.3 m to 10 m. The main characteristics of this lithofacies are abundant crinoid fragments disseminated throughout and frequently intercalating dark brown shaly partings (Fig. 61). This lithofacies is separated from SWP lithofacies because the component bioclasts are mostly crinoids and they are unique in the Dubuque Member. The size of crinoid fragments ranges from 0.5 mm to 4 mm. The brown partings are composed of anastomosing swarms of clay seams, rich in phosphate grains (Fig. 62). The phosphate grains are 31-51 μ in size, show sutured boundaries when in contact with each other. The frequency and thickness of the brown partings generally increase upward. This lithofacies occasionally contains beds of crinoidal packstone, 1-4 cm in thickness. The lower boundaries of these packstone beds are sharp to gradational while upper boundaries are always gradational. Thin-shelled brachiopods of 2-6 mm in size are also abundant in this lithofacies (Fig. 61). Bioturbation is rare.

Interpretation

This lithofacies was deposited in a lower mid-ramp to deep ramp environment. This interpretation is based on the lack of current structures, scarcity of bioturbation, and the abundance of phosphate grains indicating slow sedimentation. The occasional packstone beds seem to have been produced during storm events. The upward increase

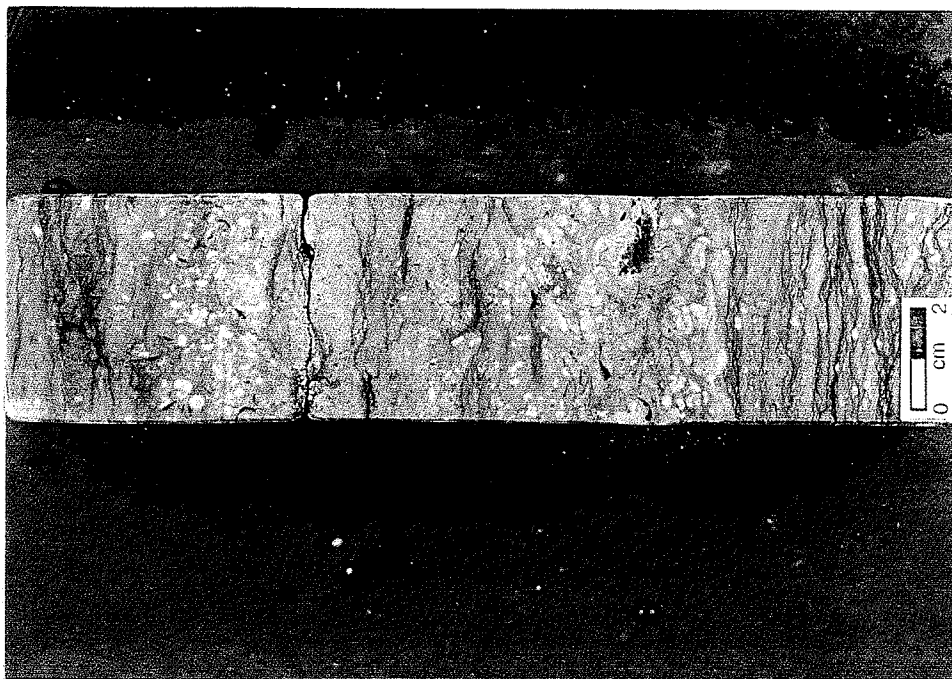


Fig. 61. Core slab photograph of the crinoidal wackestone lithofacies (CW) showing abundant dark brown argillaceous partings and crinoid fragments. Some beds are crinoidal packstone more rich in crinoid fragments. Dubuque Member. Locality WK-2. WGNHS Sample Repository BD320, 165'.

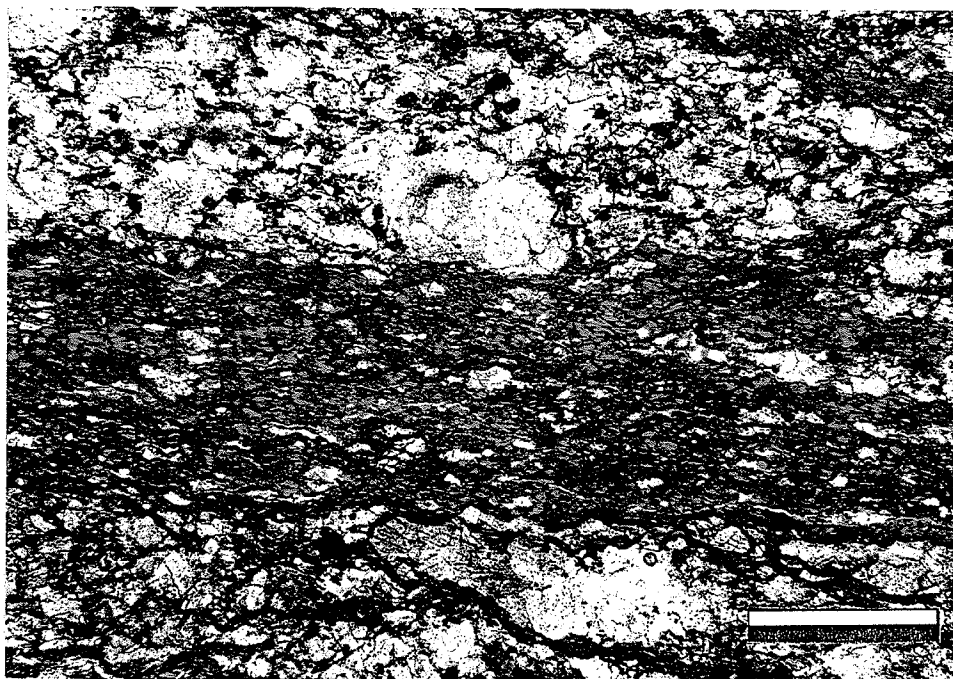


Fig. 62. Photomicrograph of the CW lithofacies showing abundant phosphate grains concentrated in the brown partings. Scale bar is 0.5 mm long. Dubuque Member. Locality JE [U.W.1896/23].

of the brown shaly partings probably indicates gradual deepening of relative sea level.

11. LITHOFACIES RELATIONS

Lithofacies characteristics indicate that the Sinnipee Group was deposited in shallow to deep subtidal environments. The interpreted depositional profile is that of a low-gradient ramp with no apparent break in slope. The ramp terminology is consistent with that of Ahr (1973), Read (1985), and Burchette and Wright (1992). The ramp model is similar to the 'continental-shelf' model (or basin model of Laporte and Imbrie, 1964) in which there is a simple linear relation of increasing water-depth away from the shore. Thus, ramp environments are based on the recognition of fair-weather wave base and storm wave base.

Figure 63 shows the general depositional environments of the Sinnipee Group carbonate sediments based on a process-oriented classification (e.g., Burchette and Wright, 1992). Relative positions of the lithofacies are plotted on the basis of the interpreted depositional environment. The ramp settings are subdivided into inner, mid-, and outer ramp environments. The inner ramp is a subtidal zone above FWB and in high-energy settings encompasses sand shoals or organic barriers and back-barrier peritidal areas. Inner ramp facies in the Sinnipee Group in the study area are rare and seem to be mostly low-energy. The mid-ramp zone extends from fair-weather wave base (FWB) to storm wave base (SWB), although the water depths that these

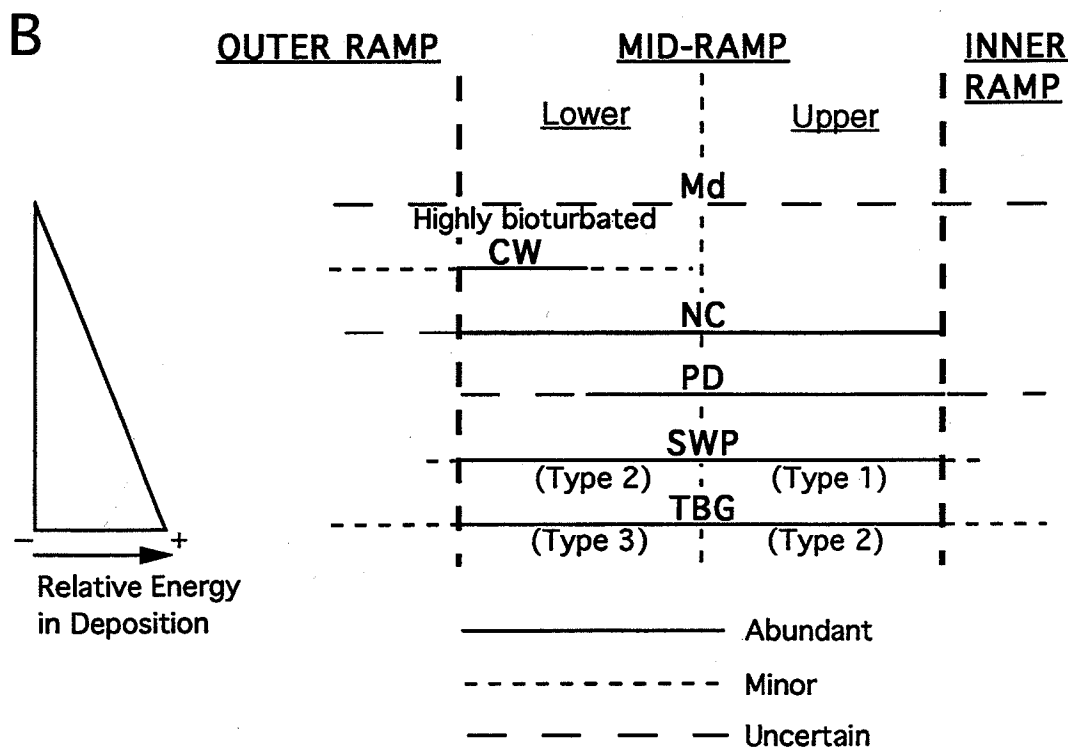
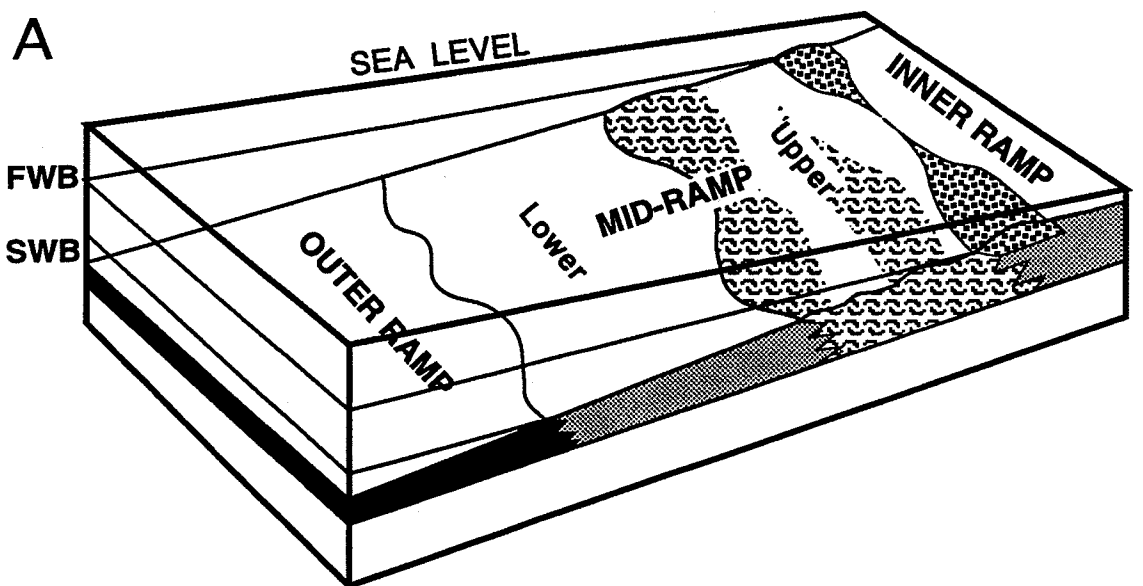


Fig. 63. Schematic diagram showing the interpreted depositional system (A), and relative position of the lithofacies in the carbonate-dominated setting of the Sinnipee Group (B). It does not reflect temporal variation of lithofacies association. Md: Mudstone; CW: Crinoidal wackestone; NC: Nodular carbonate; PD: Porous dolostone; SWP: Skeletal wackestone to packstone; TBG: Thin-bedded grainstone

boundaries represent may vary from setting to setting (Burchette and Wright, 1992). In the mid-ramp, sediments show evidence of frequent storm-reworking such as storm-generated sedimentary structures (e.g., graded beds and hummocky cross-stratification, HCS). Proximal-distal trends can commonly be recognized in ancient mid-ramp deposits (Aigner, 1985). The mid-ramp zone is further subdivided into upper and lower mid-ramp to represent the relative position of the subdivided carbonate lithofacies more accurately. The upper mid-ramp zone is characterized by more frequent storm reworking and higher content of carbonate grains, while the lower mid-ramp is characterized by less frequent storm reworking and higher content of fine material such as lime mud and clay. The sediments in the outer ramp zone show little evidence for direct storm reworking but distal tempestites may occur in the upper part (Aigner, 1985).

The Sinnipee depositional profile and the lithofacies changed through time. Generally two end members can be recognized: siliciclastic-dominated and carbonate-dominated settings. The siliciclastic dominated setting is characterized by much terrigenous clay input into the depositional site. The mid-ramp sediments contain much clay as well as lime mud in varying proportions. The carbonate-dominated setting is characterized by minor terrigenous clay input into the depositional site and by healthy carbonate production in the mid-ramp (Fig. 63). Large-scale (10's meter) gradual transition from siliciclastic-dominated settings to carbonate-dominated settings are recognized in the Sinnipee Group while the reverse transition is relatively sharp. The transitions are interpreted to reflect the long-

term sea-level fluctuation and climate which controls siliciclastic supply.

The relative influence of wave, storm, and tide is Burchette and Wright's (1992) primary criteria in their classification of carbonate ramps which is analogous with siliciclastic shelves. Degree of environmental energy, which is reflected on predominant lithology, is the additional criteria in the classification. Most carbonate ramps in the geological record were storm-dominated, which may in part reflect the relatively high frequency of storm events in the low-latitudinal settings in which most major carbonate platforms accumulate (Burchette Wright, 1992). In the storm-dominated ramp sequences, coarse, graded tempestite-rich mid-ramp successions show transition to inner ramp successions which contain shoreface barrier sediments such as ooid/skeletal grainstone and boundstone.

Some unusual ramp successions are observed in the Sinnipee Group lacking near-shore shoal belts so that inner-ramp lagoonal mudstone prograded over low-energy storm-influenced mid-ramp deposits. This unusual ramp successions in the Sinnipee Group is interpreted to be caused by unusual hydraulic conditions in which incoming oceanic waves loses their energy very gradually over wide area in a broad epeiric sea. Fairchild (1989) and Fairchild and Herrington (1989) described a similar carbonate ramp sequence from Greenland and Scotland in which low-energy, storm-influenced mid-ramp deposits passed landward into inner-ramp stromatolitic and evaporitic lagoons without intervening shoreface barrier deposits. This differs from the conventional models and is interpreted it as a

consequence of infrequency of significant wave activity. Therefore, a low-wave energy, microtidal, storm-dominated ramp model is postulated for such successions.

V. SEQUENCE STRATIGRAPHY & SEDIMENTOLOGY

1. INTRODUCTION

Interaction between eustatic sea-level changes, tectonics, accumulation rates, climate, and other complex biological and environmental factors control platform and basin evolution. The combination of these factors results in apparent changes in vertical and lateral facies transition, vertical stacking patterns, and form chronostratigraphically significant boundaries that bound genetically related strata. The main theme of this chapter is the interpretation of the depositional history of the Sinnipee Group in eastern Wisconsin in relation to those variables. To accomplish this, sequence stratigraphic approach was adopted, which emphasize the recognition of chronostratigraphically significant boundaries, and the temporal evolution of the strata and lithofacies.

Parasequence and Sequence: Concepts and Definition

Sequence stratigraphy packages genetically related strata between bounding discontinuities and their correlative conformities in a hierarchical order. Thus, application of sequence-stratigraphic analysis depends on the recognition of a hierarchy of stratal units including beds, bedsets, parasequences, parasequence sets, and sequences bounded by chronostratigraphically significant surfaces of erosion, nondeposition, or their correlative surfaces (Van Wagoner et al., 1990).

A parasequence (equivalent to small-scale upward-shallowing depositional cycle) is defined as a relatively conformable succession of genetically related beds or bedsets bounded by marine flooding surfaces or their correlative surfaces separating younger from older strata across which there is evidence of an abrupt increase in water depth (Van Wagoner et al., 1990). Parasequence is the basic building block of ramp sequences (Burchett and Wright, 1992). Correlation of marine flooding surfaces allows correlation of synchronous strata across facies changes from shelf to basin. Such a method allows the investigator to examine basin evolution in discrete time slices, and examine both vertical and lateral trends through time and space.

The depositional sequence is defined as a relatively conformable succession of genetically related strata bounded above and below by unconformities and their correlative conformities (Vail et al., 1977). An unconformity is a surface separating younger from older strata, along which there is evidence of subaerial erosional truncation or exposure (and, in some areas, correlative submarine erosion), with a significant hiatus (Posamentier et al., 1988). However, this is a very restrictive definition because evidence of subaerial exposure can be removed by wave erosion at the shoreline. Therefore in the field, evidence for subaerial exposure may be inferred (Walker, 1992).

The interaction between eustatic sea-level fluctuation and subsidence creates space available for potential sediment accumulation and is referred to as accommodation space (Jervey, 1988), which is controlled by two factors: eustatic change and tectonics. Water depth involves the integration of a third parameter,

sediment supply, with eustacy and tectonics (Posamentier et al., 1988) and the inferred water depth is based on lithofacies interpretation.

2. ANCELL AND SINNIPEE SEQUENCE STRATIGRAPHY

Introduction

Witzke and Kolata (1989) identified two large scale depositional cycles in the Ancell and Sinnipee groups in Iowa-Illinois: the St. Peter-Platteville cycle and the Galena cycles. They suggested with qualitative sea-level curve that each of these is marked by a basal transgressive episode and displays shallowing upward trend in the upper part. They also identified four smaller-scale T-R cycles in these major cycles (Witzke and Kolata, 1989).

Witzke (1993) suggested that lower Platteville (Pecatonica Member) strata in Iowa form a discrete T-R cycle overlain by two to three cycles of the McGregor Member of same magnitude. The T-R cycles are 1-10 m in thickness with duration of 0.5-1.5 Ma (Witzke, 1993).

Ross and Ross (1995) presented coastal onlap curves in the Ordovician North America which shows six major regressive episode during the Blackriveran to Shermanian stages (Fig. 64). These major regressions are interpreted to correlate with the top of the Glenwood (Joachim, 1), top of the Pecatonica (2), top of the Nachusa (3), top of Quimbys Mill (4), to top of the Decorah, (5) and middle Kimmswick (6) in the Illinois Basin (Fig 64).

However, the nature and order of the cyclicity particularly in

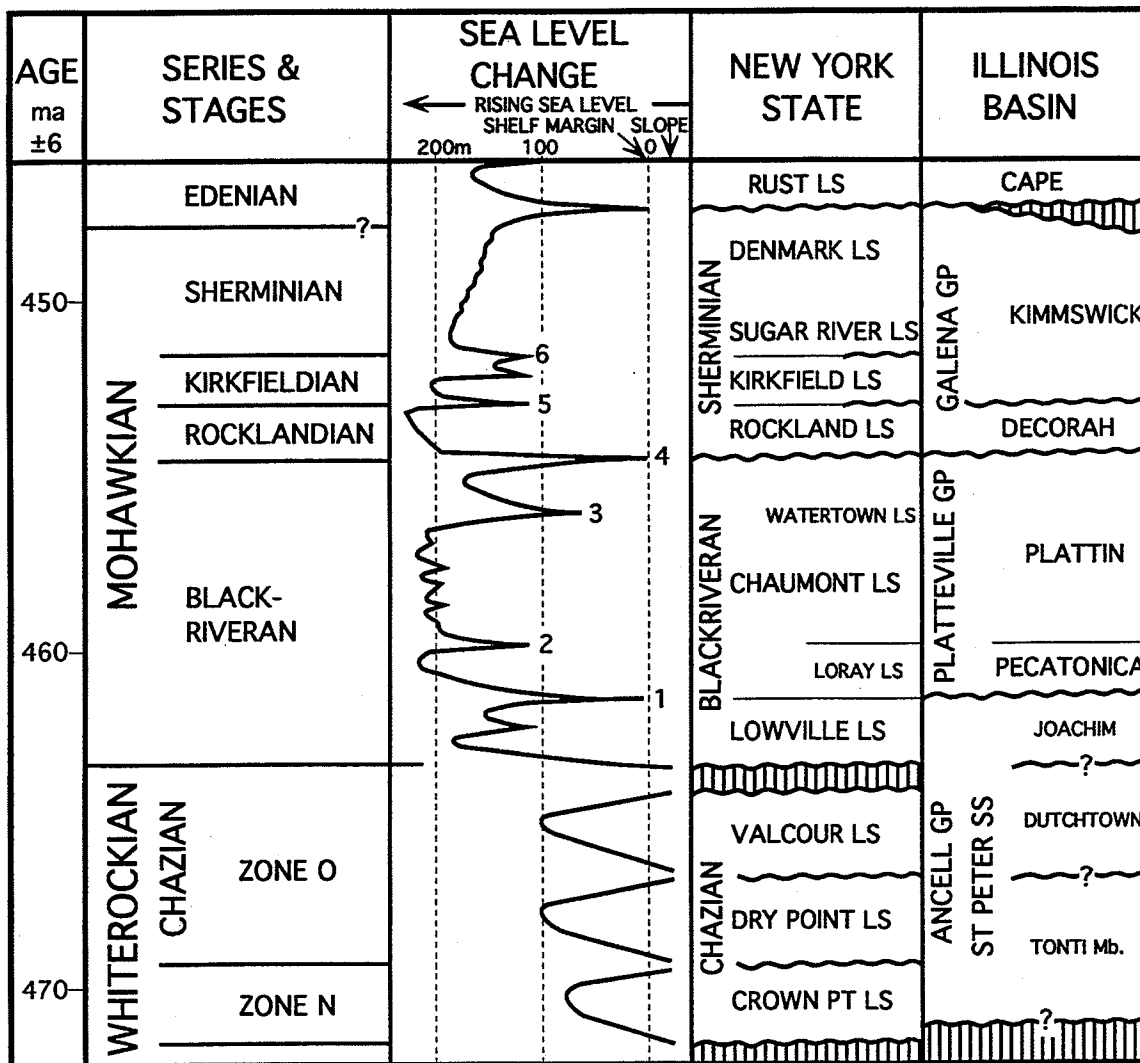


Fig. 64. Middle to Upper Ordovician sequence stratigraphy of key sections and coastal onlap curves for North America. Small numbers represent major regressions during the Blackriveran to Sherminian stages. Modified from Ross and Ross (1995).

relation to eustatic sea level change is not clear and requires further demonstration. Therefore, identification of depositional sequences in the Ancell and Sinnipee groups in eastern Wisconsin and interpretation of the sequences in relation to sea level and climate change, carbonate growth, and siliciclastic supply is the main subject of this chapter.

Parasequence and Sequence Evolution

Four depositional sequences are identified from the base of the Ancell Group (Tippecanoe Sequence boundary) to the top of the Galena Formation (Table 9; Figs. 65, 66). Table 9 lists the lithofacies associations with the main characteristics and parasequences and sequences in the Ancell and Sinnipee groups in eastern Wisconsin. Figure 67 shows the interpreted correlation of the sequences and parasequences recognized in the Ancell and Sinnipee groups in eastern Wisconsin to the Ross and Ross's (1995) sea-level curve. Sequence S1 is bounded below by the unconformity (S.B.0) on top of the PDC Group and above by the minor unconformity (S.B.1) on top of the Pecatonica Member (Fig. 65). The S.B.0 is an angular and karst unconformity formed on the PDC Group limestones and sandstones (Fig. 8). This unconformity represents about 15 m.y.'s time gap between the Sauk Sequence and Tippecanoe Sequence (Fig. 2; Sloss, 1965). During this long span of time the entire north American craton was exposed and weathering, solution, and erosion began to remove earlier Ordovician carbonates (Dott and Prothero, 1994). The eolian St. Peter Sandstone filled the paleovalley formed by the erosion and is interpreted to have been trapped during the Tippecanoe transgression. Sequence S1 shows the transition from

STAGE	FORMATION	Member/ sub-member	MAIN L.F.	BIO- TURBATION	CLAY CONTENT	STORM BEDS (Abundance)	PS	SQ
EDENIAN	GALENA	Dubuque Member	CW	Weak	Moderate	Rare	P10	S4
KIRKFIELD to SHERMANIAN		Wise Lake Member	PD/ Md	Weak to moderate	None	Moderate to rare (gradually decrease up- section)		
		upper Dunleith sub-member	PD/ SWP	Moderate	None to moderate	Common (about 20% of total thickness)	P8	
		Ion sub-member	TBG/ Sh	Moderate to strong	Slight to shaly	Abundant (up to 50% of total thickness)	P7	
ROCK- LANDIAN	DECORAH	Guttenberg Member	TBG	Weak to Moderate	Slight to moderate	Abundant (up to 71%)		S3
BLACK- RIVERAN	PLATTE- VILLE	Nachusa Member	PD	Moderate	None	Rare to Moderate	P6	S2
		Grand Detour Member	Md	Weak to strong	Slight	Moderate to rare (gradually decrease up- section)	P5	
		Mifflin Member	NC	Pervasive	Very argillaceous	Common (about 20% of total thickness)	P4	
		Pecatonica Member	Md	Weak to moderate.	Slight to moderate	None	P3	
	ST. PETER	Glenwood Member	SWP	Pervasive	None	None	P2	S1
			SC	Pervasive	None	Rare		
Sh		None	Shale	Rare	P1			
		MS	Strong	None to slight	Rare			
		LS	None	None	None			

Table 9. Lithofacies associations and main lithologic characteristics, parasequences, and depositional sequences recognized in the Ancell and Sinnipee groups in eastern Wisconsin. PS: Parasequence; SQ: Sequence. See table 2 for lithofacies code.

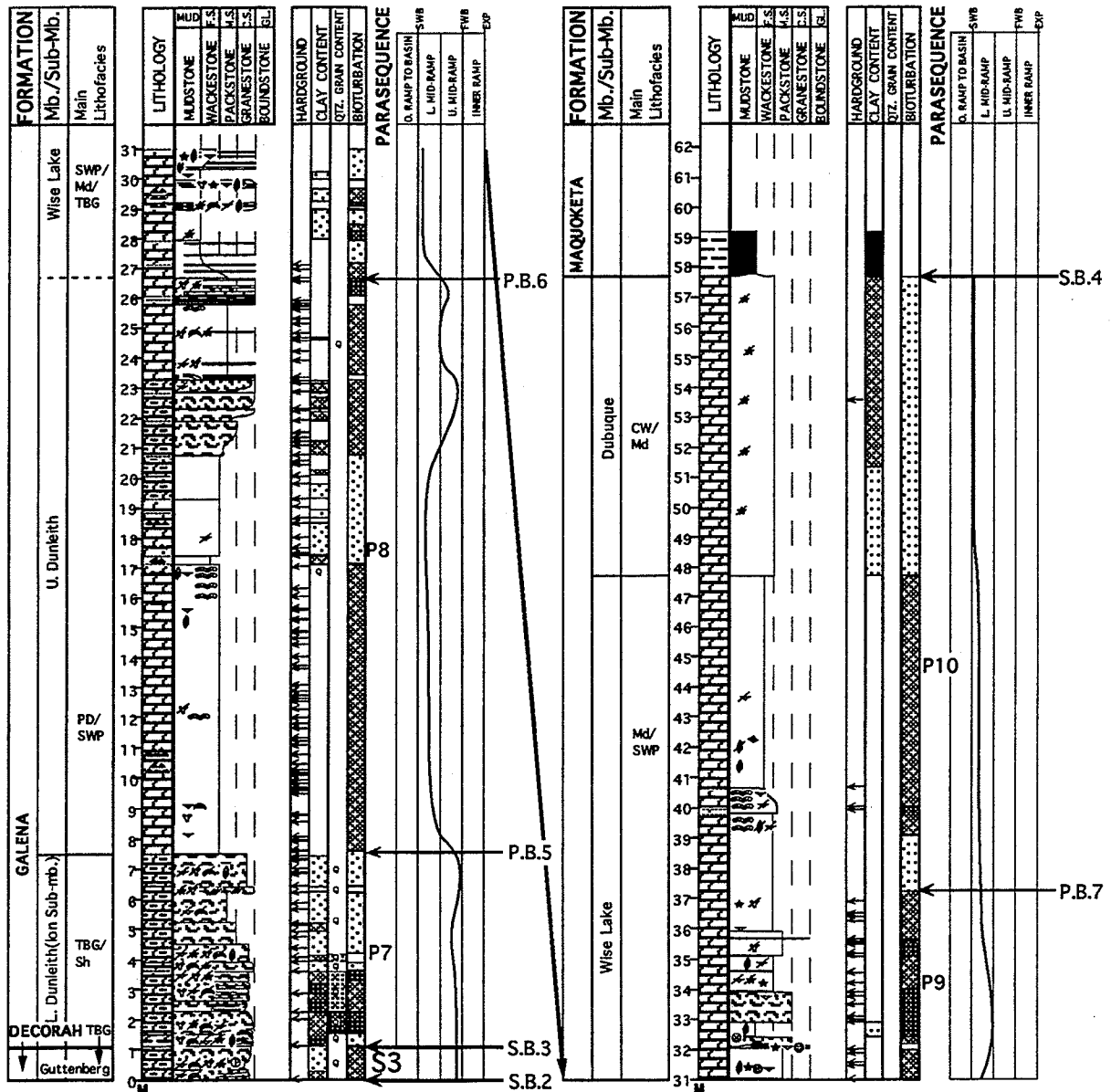


FIG. 66. Composite Section of the Decorah to Galena formations in eastern Wisconsin showing relative sea-level change, and identified parasequence and sequence boundaries (P.B., S.B.). SWB: storm wave base; FWB: fair-weather wave base; EXP: exposure. Key in Figs. B-1, 2.

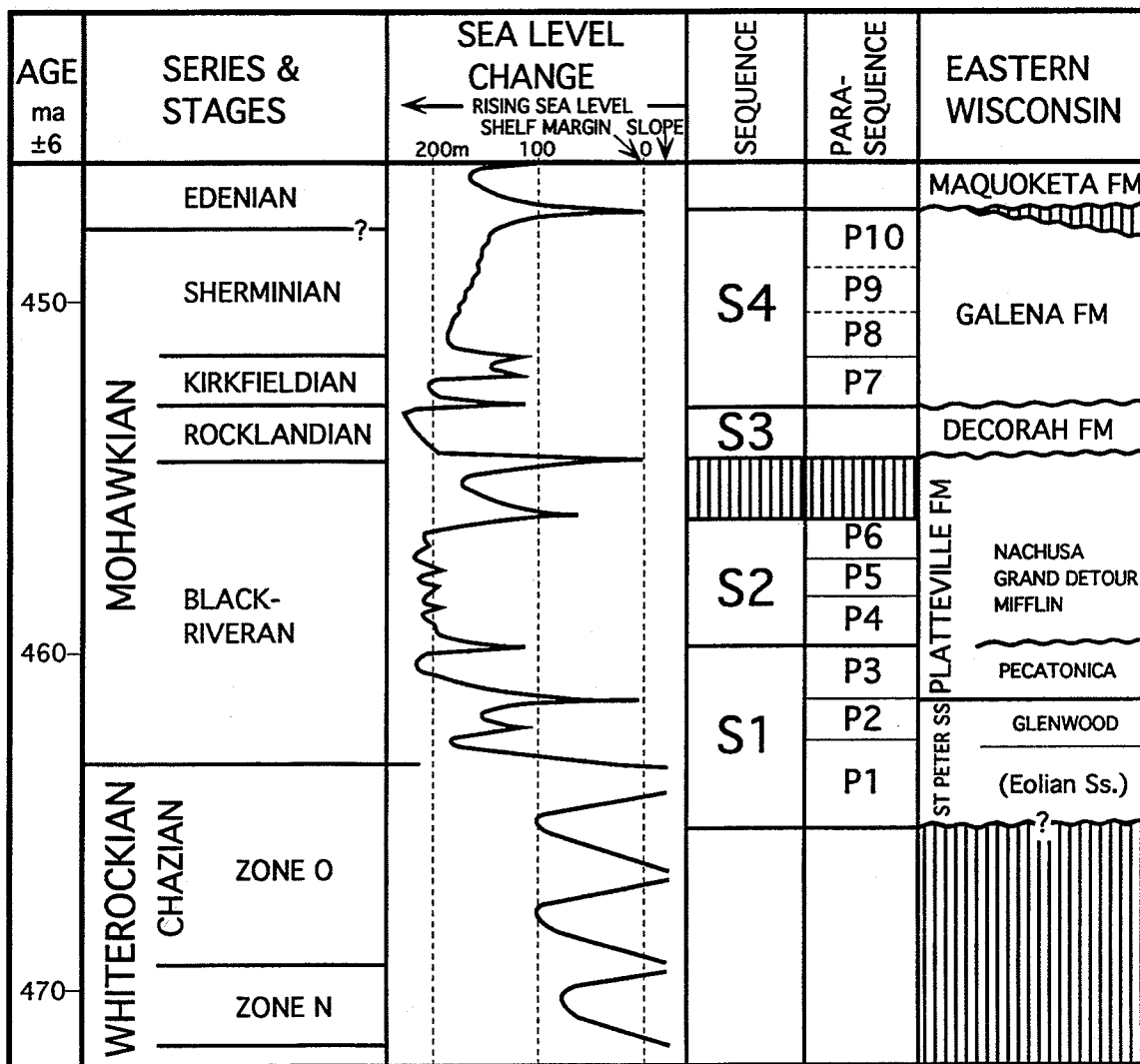


Fig. 67. Ancestral and Sinnipee groups sequence stratigraphy in eastern Wisconsin and correlation to coastal onlap curve for North America. Sea-level curve adopted from Ross and Ross (1995).

siliciclastic-dominated St. Peter Formation to carbonate-dominated Platteville Formation (Table 9; Fig. 65).

Sequence S2 is bounded below by the sequence boundary S.B.1 and above by the sequence boundary S.B.2. The S.B.1 corresponds to an inferred minor unconformity on top of the Pecatonica Member. This unconformity probably corresponds to the major regression in the middle Blackriveran in the Ross and Ross's (1995) sea level curves (Fig. 67). Sequence S2 shows a transition from terrigenous clay- and tempestite-rich bottom to carbonate-dominated top (Table 9; Fig. 65).

Sequence S3 is bounded below by the sequence boundary S.B.2 on top of the Platteville Formation and above by the sequence boundary S.B.3 on the top of the Decorah Formation (Fig. 66). The S.B.2 is an unconformity formed on top of the Platteville Formation, which corresponds to the prominent regression at the end of Blackriveran (Fig. 67). This unconformity indicates retreat of sea from the Wisconsin Arch after deposition of the Platteville Formation. Although the retreat of the sea is related with long-term sea-level fluctuations, a major uplift of the Wisconsin Arch seems to have taken place after deposition of the Platteville Formation. In general, the Galena Group strata thin to the south in Iowa and Illinois whereas the Platteville strata thickens to the south in Wisconsin and Illinois (Witzke and Kolata, 1989, Figs. 3, 4). This is interpreted by Witzke and Kolata (1989) to be indicative of major structural changes in the Midwest that accompanied the initiation of the Galena Group deposition. Therefore, the uplift of the Wisconsin Arch is interpreted as part of the structural changes and these structural changes are probably related to the Taconic Orogeny to

the east. This interpretation is also supported by the abundant volcanic ash beds in the Decorah Formation in southwestern Wisconsin derived from the east (Witzke and Kolata, 1989).

The S.B.3 is a minor unconformity which corresponds to the regression at the end of Rocklandian (Fig. 67). General upward and southward decrease in clay content is recognized in sequence S3. Sequence S3 is relatively thin and pinches out to the north of Jefferson county (Appendix C).

Sequence S4 is bounded below by the sequence boundary S.B.3 on top of the Decorah Formation and above by the sequence boundary S.B.4 on the top of the Galena Formation (Fig. 66). The S.B.4 is an unconformity formed on top of the Galena Formation and this unconformity is widely recognized in most of North America (Fig. 64). Sequence S4 shows an overall transition from siliciclastic-dominated bottom rich in tempestites to carbonate mudstone-dominated upper part (Table 9; Fig. 66). Also observed in sequence S4 is an increase in argillaceousness to the north (Appendix C).

Sequence S1

Three parasequences are identified in the sequence S1. The main lithofacies are laminated sandstone, massive sandstone, shale, sandy carbonate, skeletal wackestone to packstone, and mudstone in ascending order (Table 9; Figs. 68, 69). This sequence shows a transition from the siliciclastic-dominated St. Peter Formation (P1) to carbonate-dominated Platteville Formation (P2, P3) as marine transgression continued over the Wisconsin Arch. A general

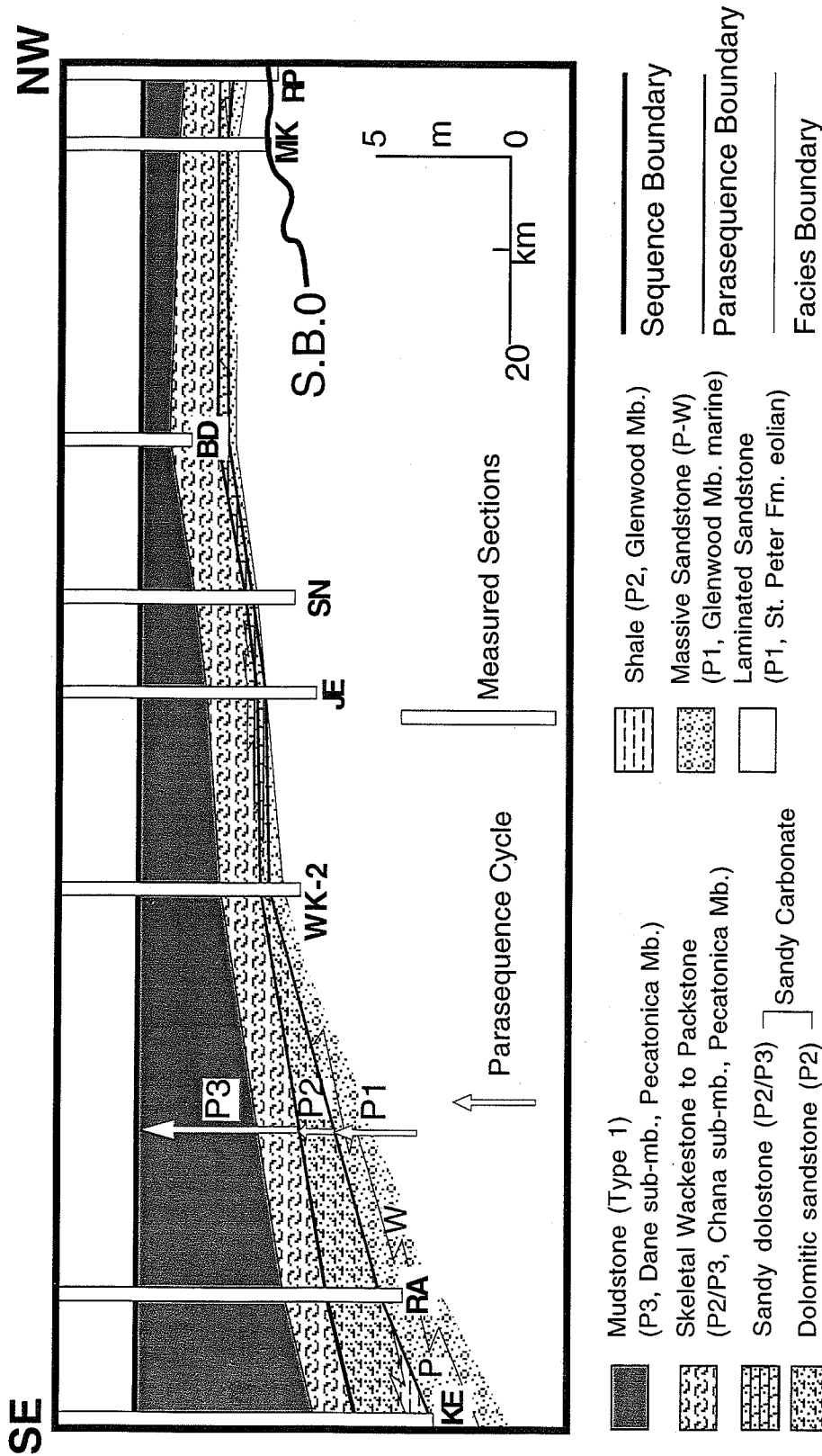


Fig. 68. Schematic cross section of sequence S1, comprising three parasequences (P1-P3). Vertical scale is exaggerated. Datum is top of S1. The upper P3 (Dane sub-member) is more bioturbated and argillaceous to the south. Note the irregular thickness variation of the Dane Sub-member. SN: Sun Prairie Qr., locality 17; BD: Beaver Dam Qr., locality 5; MK: Markesan Qr., Locality 12; RP: Ripon Qr., Locality 14; P: poorly sorted type; W: moderate- to well-sorted type massive sandstone lithofacies.

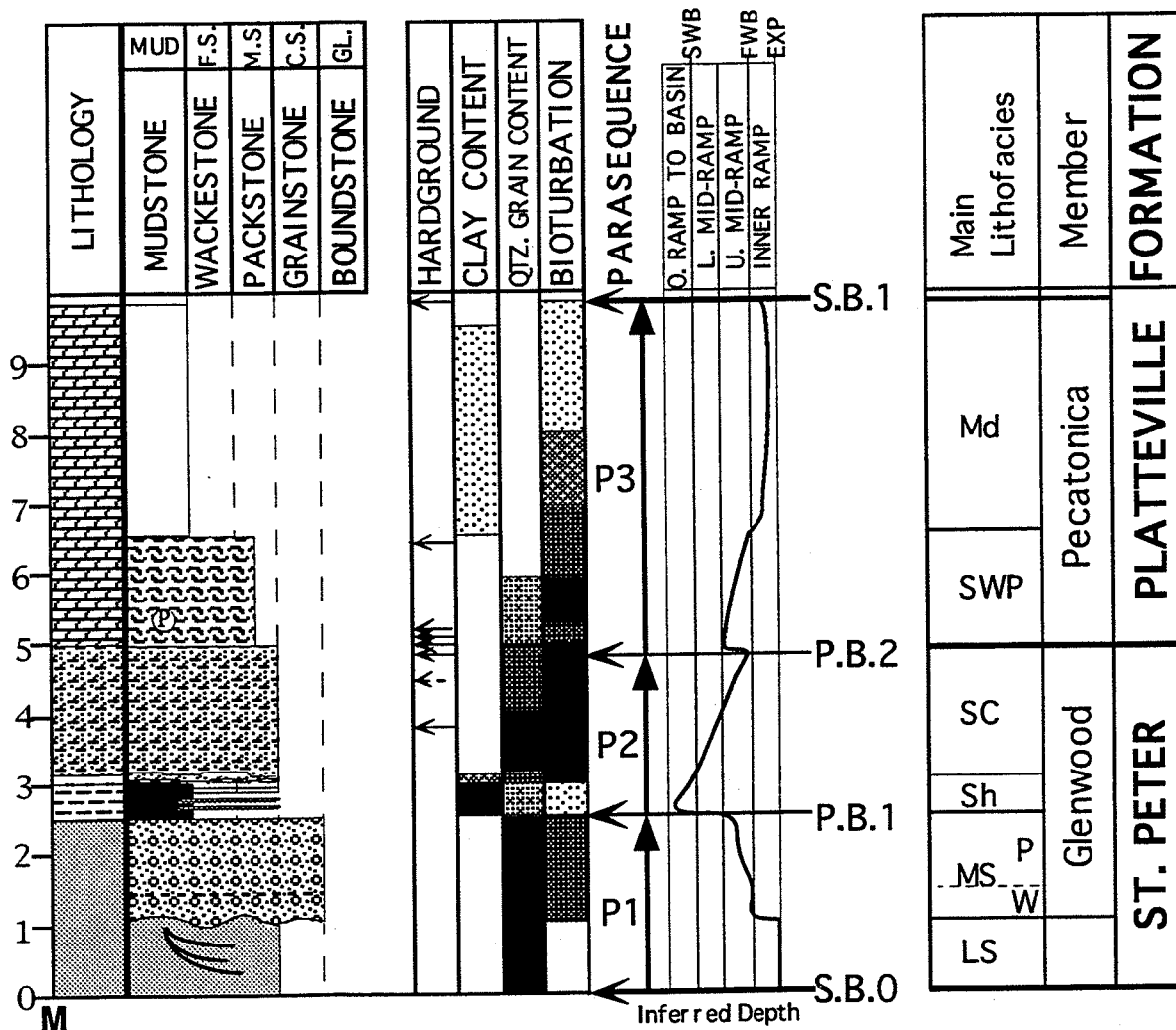


FIG. 69. Composite section of sequence S1 and relative sea-level curve. Three parasequences (P1 - P3) are recognized in this sequence. P: poorly sorted; W: well sorted. SWB: storm wave base; FWB: fair-weather wave base; EXP: exposure. Key in Figs. B-1, 2.

depositional deepening (P1) and shallowing (P2-P3) upward trend is recognized in the S1 sequence (Fig. 69).

Parasequence P1

Parasequence P1 is bounded below by S.B.0 and above by P.B.1. The lower portion of the parasequence consists of eolian sandstones of the St. Peter Formation. It is highly variable in thickness due to the nature of the unconformity (Fig. 8). The eolian sandstone is bounded above by a ravinement surface with occasional reworked pebbles derived from the underlying eolian sandstones (Long, 1988) representing initial marine transgression. The upper portion of parasequence P1 consists of the massive marine sandstone lithofacies. The poorly cemented eolian sandstones of the St. Peter Formation were subject to wave erosion and bioturbation during transgression. Parasequence P1 represents initial transgressive marine deposits over the Wisconsin Arch at the base of the Tippecanoe sequence.

Long (1988) described trough cross-bedded marine sandstone lithofacies and subdivided this lithofacies into two sub-facies bounded by a FCT (fine-to-coarse transition) surface. The lower sub-facies is well sorted, fine-grained quartz-arenite whereas the upper sub-facies is poorly sorted and coarse-grained. He suggested that the poorly sorted quartz-arenite might have different source other than eolian debris. In specific, he mentioned that the clay-rich poorly sorted sands were transported to the south by longshore currents from alluvial source in the north (Long, 1988; Figs. 70, 71). The FCT surface terminates to the positive area (Fig. 71). The FCT surface is not

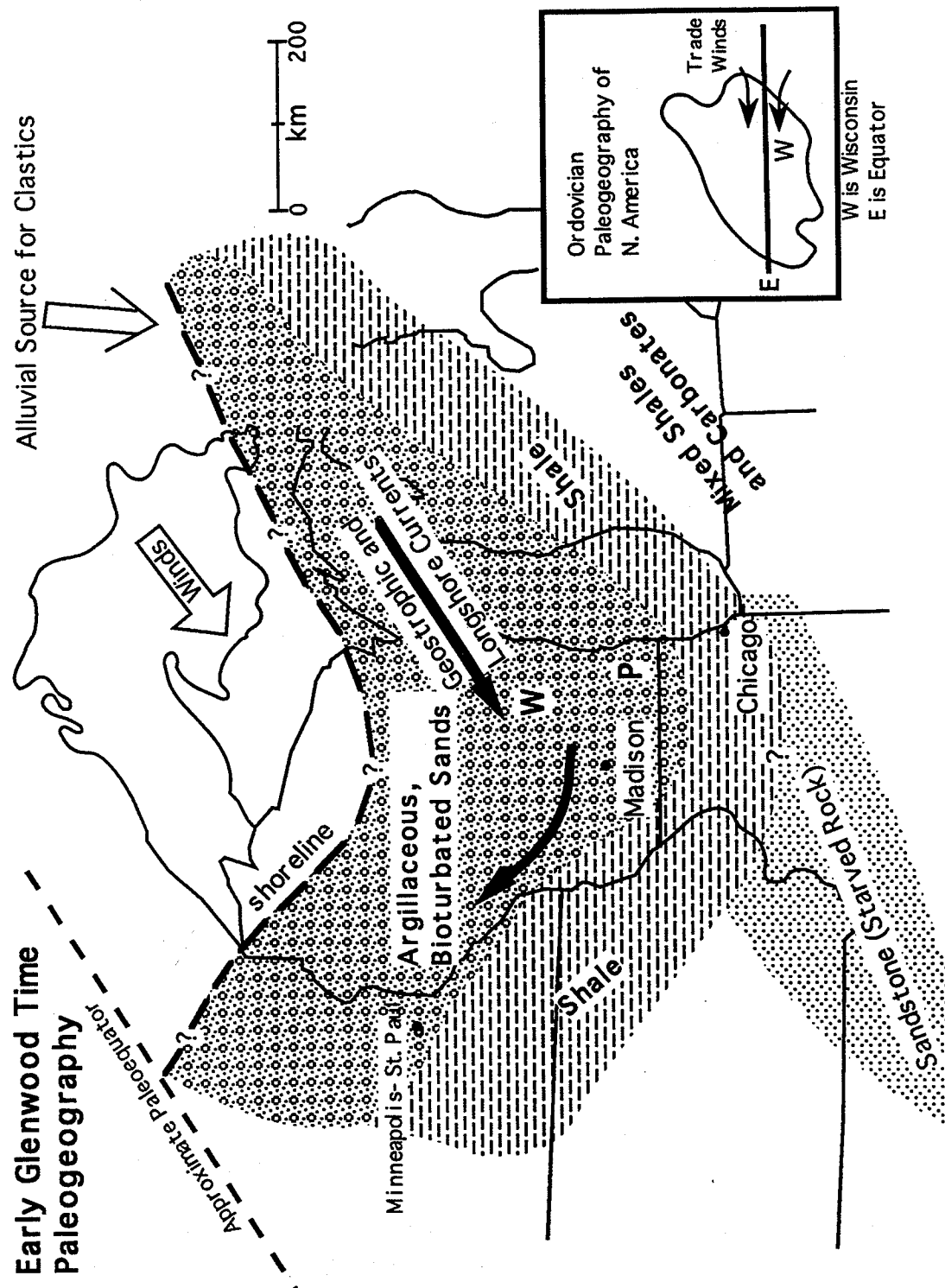


Fig. 70. Paleogeographic map of Wisconsin during early Glenwood time (P1). Modified from Long (1988) and Witzke (1980). Note the boundary between the shale and the bioturbated sands. This boundary further moved to the north in P2. P: poorly sorted, W: well sorted.

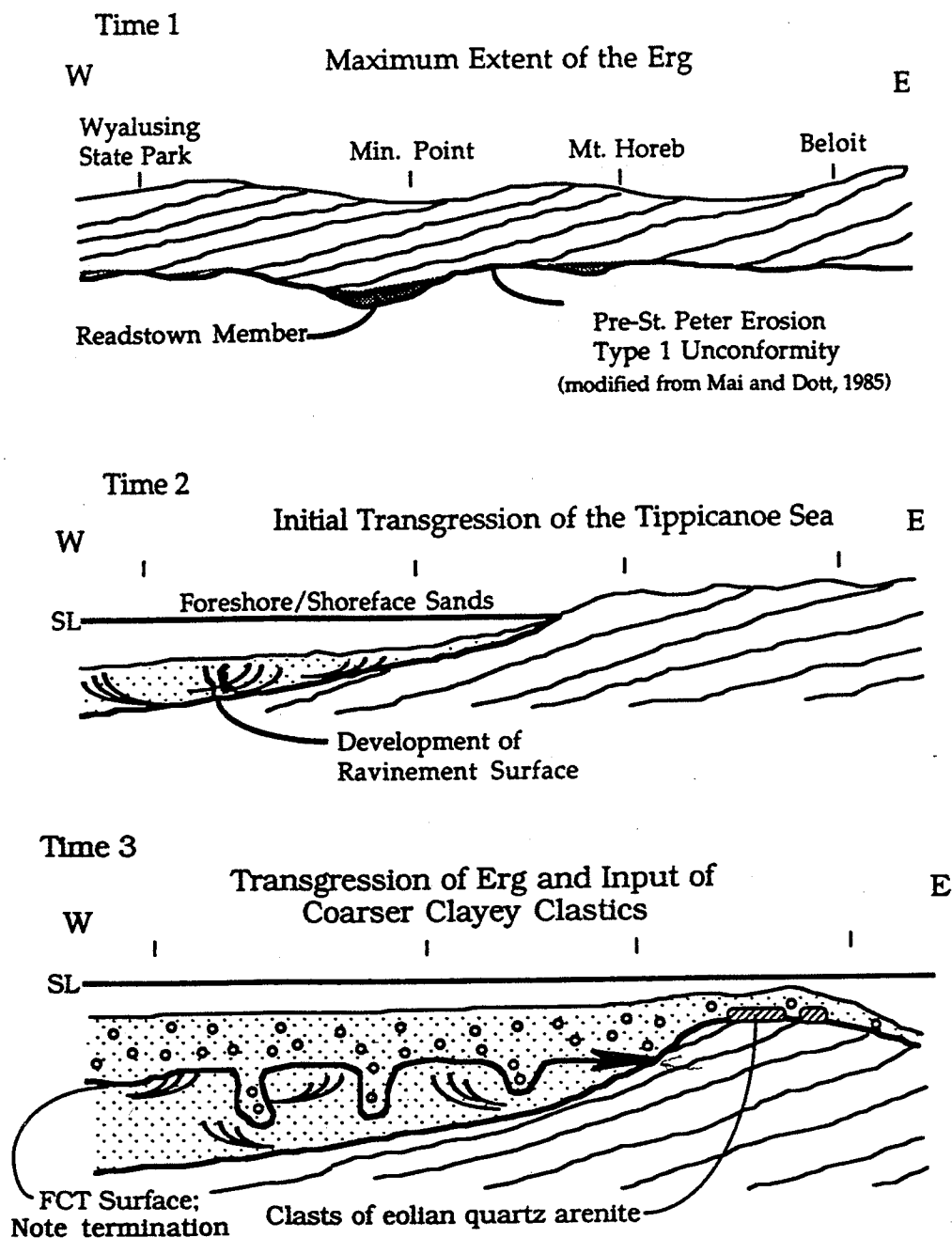


Fig. 71. Changes in sedimentation in southwestern Wisconsin during early Glenwood time (Long, 1988). Times 1 to 3 represent diagrammatic sketches showing the evolution of the uppermost St. Peter to lower Glenwood strata as sea level rises. Note the onlapping of the FCT surface. No occurrence of the FCT surface in eastern Wisconsin is probably due to higher elevation of the sea floor in eastern Wisconsin.

recognized in the study area probably because of higher elevation of eastern Wisconsin during Glenwood time.

In eastern Wisconsin, the eolian, laminated sandstone lithofacies (LS) is overlain by the bioturbated, massive marine sandstone lithofacies (MS). The massive marine sandstone lithofacies corresponds to the poorly sorted, coarse-grained quartz arenite of the trough cross-bedded lithofacies. The ravinement surface is recognized as a jagged boundary between the two lithofacies (Figs. 28, 69) although the erosional truncation is not clear in most outcrops probably due to obliteration by bioturbation. The massive sandstone lithofacies (MS) can be subdivided into poorly-sorted and moderate- to well-sorted types, and their occurrences show regionally different distribution (Fig. 68). The well-sorted type probably was deposited in a wave-agitated environment during initial marine transgression. Gradual increase in the relative sea level resulted in deposition of the poorly-sorted type. Both types of the massive sandstone lithofacies correlates to the poorly sorted, coarse-grained quartz-arenite of Long (1988) based on the grain size and the *Chondrites* burrows, and probably had same source. Therefore, the change from the well-sorted type to the poorly-sorted type may represent change in water depth rather than source change. The restricted occurrence of the poorly-sorted type to the south is indicative of higher elevation to the north and shallower water sediments (Fig. 68).

Parasequence P2

Parasequence P2 is bounded above by P.B.1 and below by P.B.2 (Fig.

69). P.B.1 is sharp and slightly irregular, and occurs at the base of a shale or sandy carbonate lithofacies with thin shale laminae rich in phosphate grains. Parasequence P2 shows a shallowing upward trend that is interpreted as the progradation of a sandy carbonate complex.

The shale lithofacies in the Glenwood Member represents the highest relative sea level in the study area during the Ancell time. The dark brown shale laminae, which is correlated over much of the study area, is interpreted to represent starved sedimentation during transgression. The restricted occurrence of the shale lithofacies in the southeastern study area (Kenosha County) indicates increasing paleowater depth to the southeast (Fig. 68). In a more shoreward direction, quartz sands were deposited with minor lime mud accumulation and gradually prograded offshore as accommodation space decreased. The vertical succession of P2 shows a gradual increase in quartz grains above shale followed by a decrease in quartz grains and increase in carbonate content (Fig. 30). The lime mud production increased as siliciclastic supply decreased.

Skeletal wackestone to packstone occurs locally in the north in areas of little siliciclastic input (Fig. 68). Correlation of the skeletal wackestone to packstone in the north to the sandy dolostone in the south is based on the observation that the sandy dolostone rapidly pinch out in short distance (Fig. 6, compare Locality 12 with 14). The occurrence of the sandy dolostone seems to depend on the local supply of the siliciclastics which might be related with the local hydrodynamic regime.

Parasequence P3

Parasequence P3 is bounded below by P.B.2 and above by S.B.1 (Figs. 68, 69). P.B.2 is the lowermost hardground of the hardgrounds separating the sandy carbonate lithofacies below and the skeletal wackestone to packstone lithofacies above (Fig. 69). Parasequence P3 consists mostly of the skeletal wackestone to packstone lithofacies overlain by the Type 1 mudstone lithofacies (Fig. 68). The skeletal grainstone to packstone lithofacies in parasequence P3 is interpreted to have been deposited in a upper mid-ramp below fair-weather wave base with a little siliciclastic input.

The lower portion of P3 represents the gradual transition from a mixed siliciclastic-carbonate to a carbonate-dominated system. This is interpreted to represent an increase in accommodation space related to a regional sea level rise (Witzke and Kolata, 1989). The decrease in the siliciclastic input is evidenced by the upward decrease in sand-sized quartz grains in this lithofacies.

The upper portion of P3 consists of Type 1 mudstone lithofacies showing an upward increase in bed thickness (Fig. 15) and a decrease in clay content. The mudstone lithofacies is interpreted to have been deposited in a protected environment with open circulation based on open marine fauna. The wavy, irregular beds truncating underlying beds in the lower part of the mudstone lithofacies probably indicate deposition under intermittent high energy conditions such as migration of small tidal channels or storm wave erosion in a lagoonal environment. Overlying mudstone with thicker, planar beds may have been deposited in a more protected environment. Gradual filling of

accommodation space with lagoonal mudstone resulted in a shallowing upward trend in parasequence P3.

Overall parasequence P3 shows a shallowing upward depositional trend in which the upper mid-ramp skeletal wackestone to packstone lithofacies overlain by the inner-ramp lagoonal mudstone lithofacies. Reconstruction of this ramp succession based on Walther's law depicts storm-influenced mid-ramp sediments pass landward into low-energy inner-ramp sediments without intervening barrier. This differs from conventional models and can be explained as a consequence of low wave energy. Similar ramp successions are shown in Parasequence P4 and the unusual low wave-energy, microtidal, storm-dominated ramp sequences observed in the sequence S1 and S2 are further discussed in P4.

The common occurrence of the ferruginous hardground along the lower boundary of P3 (Figs. 6, 69) indicates decreased or inhibited sedimentation. Long (1988) related the development of the hardground with a fastest rate of sea-level rise during the Tiptecanoe transgression. The repetitive nature of hardgrounds near the base of P3 is probably related with punctuated inhibited sedimentation during an overall transgression. The origin of the hardgrounds is further discussed in Ch. VI.

Sequence S2

The sequence S2 is bounded below by the sequence boundary S.B.1 and above by the sequence boundary S.B.2 (Figs. 72, 73). S.B.1 corresponds to an inferred minor unconformity on top of the Pecatonica Member. Its recognition is based on:

- (1) the hardground on top of the Pecatonica Member is widely correlated over much of the Midwest (Templeton and Willman, 1963; Byers, 1983; Mossler, 1985; Wilcer, 1989);
- (2) the strata above the Dane sub-member (New Glarus, Medusa, Oglesby), which comprise shallow-water facies, are missing in eastern Wisconsin (Fig. 12);
- (3) the thickness of the Dane sub-member is highly variable whereas the underlying Chana sub-member and overlying Mifflin Member show continuous thickening trend to the south (Fig. 6), indicating possible erosion of the Dane sub-member;
- (4) the overlying Mifflin Member appears to show onlapping relationship to the unconformity surface (Fig. 6).

The sequence boundary S.B.1 is interpreted to have formed during relative sea-level fall. Evidence of subaerial exposure is lacking, which is probably due to wave base erosion during the following transgression (e.g., Plint, 1988). The hardground developed on the unconformity surface is interpreted to have formed diachronously in the zone above FWB by wave-inhibition of sedimentation during transgression (Fig. 74).

Sequence S2 comprises three parasequences, P4, P5, and P6 (Fig. 73). The main lithofacies in this sequence are the nodular carbonate, mudstone, porous dolostone, and thin-bedded grainstone lithofacies (Table 9; Fig. 73). Sequence S2 shows a depositional shallowing upward trend from a mid-ramp setting to an inner ramp setting with minor relative sea-level fluctuations (Fig. 73). Sequence S2 shows a transition from terrigenous-rich base to a carbonate-dominated environment at the top.

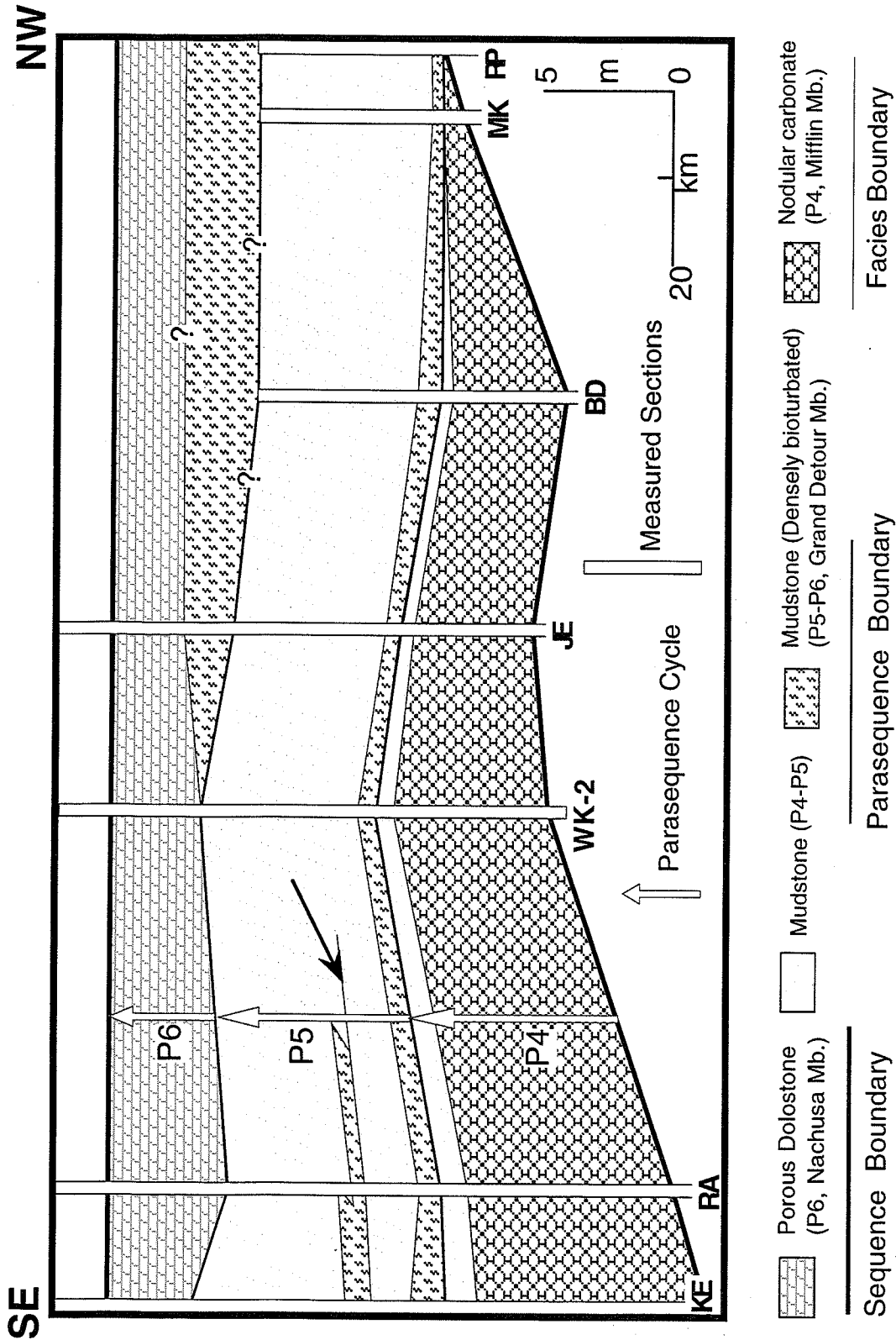


Fig. 72. Schematic cross section of sequence S2. Vertical scale is exaggerated. Note the intertonguing of two types of mudstone in P5 in the south. Datum is top of S2. BD: Beaver Dam Qr., locality 5; MK: Markesan Qr., Locality 12; RP: Ripon Qr., Locality 14.

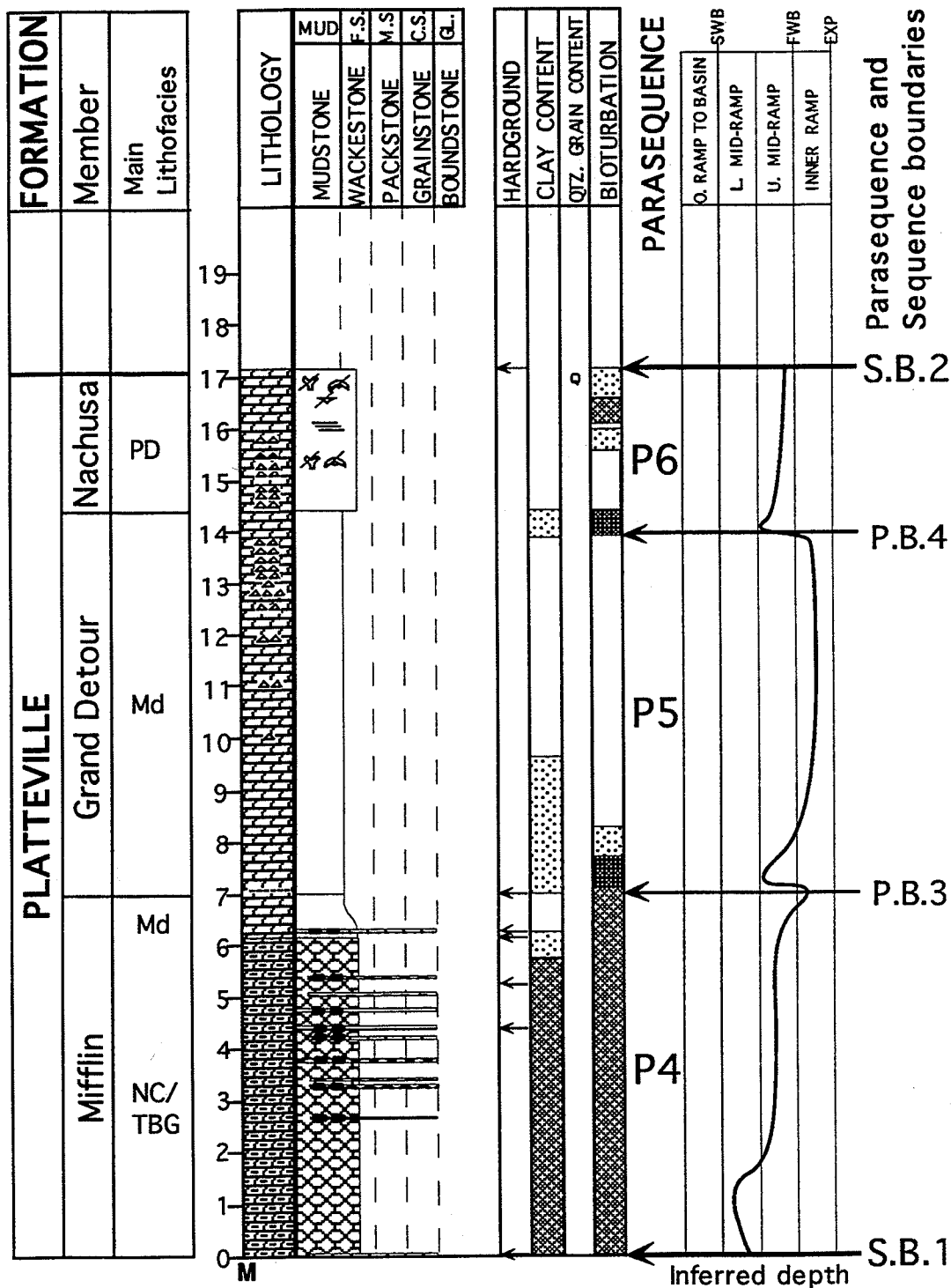


FIG. 73. Composite section of sequence S2 and relative sea-level curve. Three parasequences (P4 - P6) are recognized. SWB: storm wave base; FWB: fair-weather wave base; EXP: exposure. Key in Appendix B, Fig. B-1, 2.

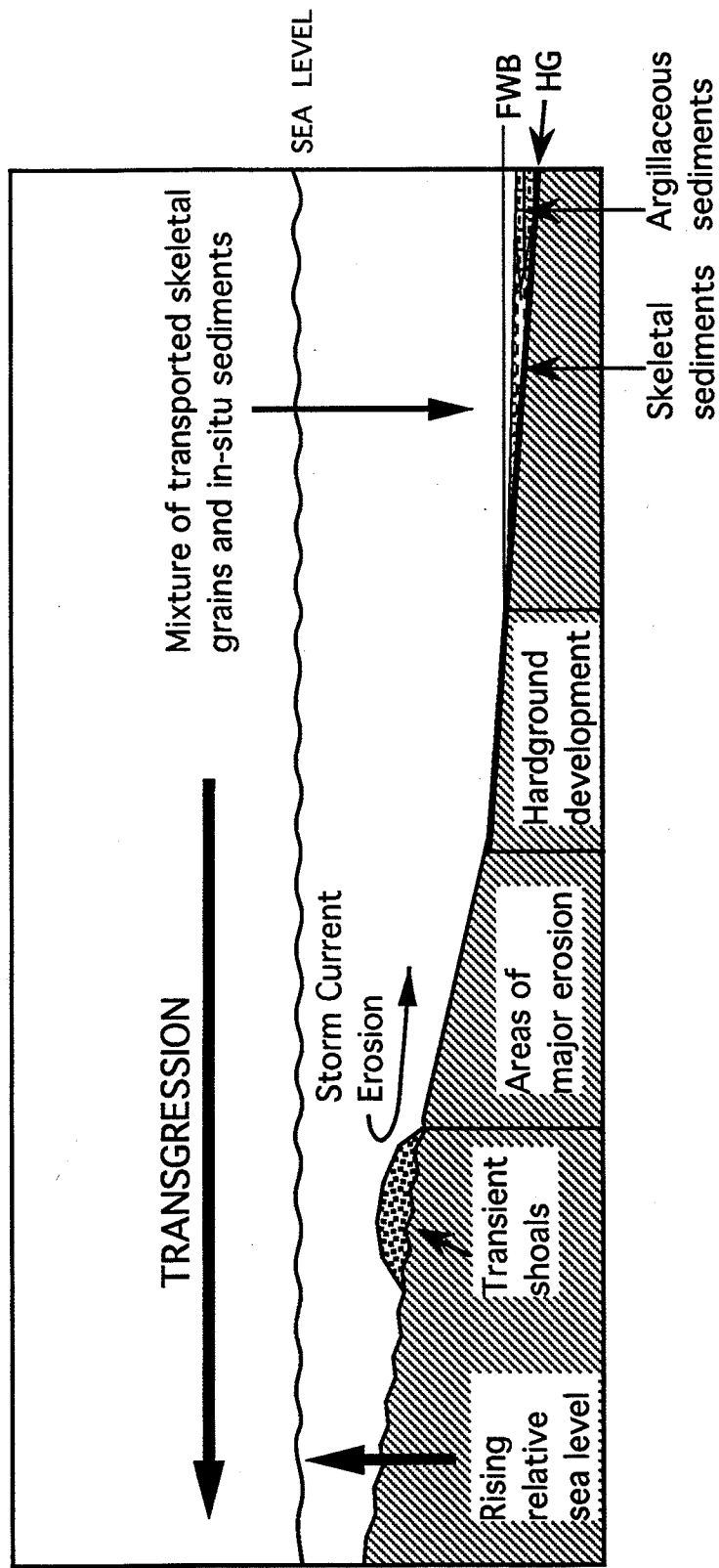


Fig. 74. Mechanisms of wave erosion and hardground development during a transgression by shoreface retreat during P4. HG: hardground.

Parasequence P4

Parasequence P4 is bounded below by the sequence boundary S.B.1 and above by the parasequence boundary P.B.3 (Figs. 72, 73). This parasequence consists of nodular carbonate, thin-bedded grainstone, and Type 2 mudstone lithofacies (Figs. 72, 73). Figure 74 shows the interpreted depositional setting of parasequence P4. Gradual landward retreat of the shoreface eroded the previous sediments and hardground developed on the eroded surface above the FWB (Fig. 74). The nodular carbonate lithofacies was deposited below FWB. Intermittent storms reworked the nodular carbonate and the sediments above FWB and transported the skeletal grains (Type A bioclasts) from the shoals into deeper areas. Thin-bedded grainstone lithofacies were deposited in the mid-ramp (Fig. 74). The interpreted skeletal shoals developed during the transgression were probably small and relatively less-cemented because shoreface retreat inhibited large skeletal shoals to form. Thus those skeletal shoals were transient and were not preserved in most transgressive sediments.

A generally shallowing upward trend is recognized in this parasequence based on gradual upward increase in grainstone beds (Fig. 72). The upward increase in the grainstone beds and general upward decrease in the clay content suggest a shallowing upward trend as sediments prograded. Mudstone lithofacies (Type 2) caps parasequence P4 (Fig. 73) and is interpreted to have been deposited in a protected and possibly restricted environment based on the scarceness of fauna, bioturbation, and sedimentary structures. The restriction and deposition of the mudstone lithofacies is interpreted to occur as

accommodation space as well as the energy of the ramp decreased.

Parasequence P4 is unusual in that high-energy shallow-water shoals are not observed in this regressive succession in spite of the storm beds observed in the lower to middle part of the parasequence. These unusual ramp successions observed in parasequence P4 as well as in P3 are attributed to an unusual hydraulic conditions due to low-wave energy in the shoreface during deposition of S1 and S2 sequences. It is speculated that incoming oceanic waves loses their energy gradually over wide area in the broad epeiric sea. A barrier is not required to separate lagoonal and shoreface sediments in a setting where wave and tide energy are low (Fairchild and Herrington, 1989). The sedimentary record of parasequence P4 clearly indicates that the power of storms must have decreased landward, so that the leading margin of the lagoon must have been sufficiently shallow to absorb much of the wave energy. Fairchild and Herrington (1989) and Fairchild (1989) have described an unusual low-wave energy, microtidal, storm-dominated ramp from the upper Proterozoic of Greenland and Scotland. This regime generated a succession lacking near-shore shoal belts, so that low-energy, storm-influenced mid-ramp deposits passed landward into inner ramp stromatolitic and evaporitic lagoons via a zone of storm-reworked sediments rich in intraclastic grainstone beds (Fairchild and Herrington, 1989).

The prominent hardground on top of P4 is interpreted to represent longer duration of non-deposition during transgressive period. This interpretation is based on that the hardground is very prominent formed on a parasequence boundary and that this hardground is correlated

widely over the study area (Fig. 6).

Parasequences P5

Parasequence P5 is bounded below by P.B.3 and above by P.B.4. The P.B.3 is a prominent hardground, but sometimes the hardground is missing and the P.B.3 is gradational being identified by a rapid increase in the degree of bioturbation. Parasequence P5 consists mainly of mudstone lithofacies (Type 2). The mudstone lithofacies is subdivided into two types: the dark gray, slightly to moderately argillaceous, strongly bioturbated mudstone, and the light purplish gray, argillaceous-free to slightly argillaceous mudstone sublithofacies. The strongly bioturbated, dark gray mudstone is interpreted to have been deposited in deeper water settings during transgression that enabled open circulation and slower rates of sedimentation. This interpretation is based on the wide-correlation of the dark gray mudstone over the study area, which is the characteristics of transgressive deposits (Fig. 72). The high degree bioturbation is related to more frequent animal activity due to open circulation and/or decreased sedimentation rate. The light purplish brown mudstone lithofacies was deposited in a shallower, lower energy and restricted environment during times of lower accommodation space.

Parasequence P5 shows a shallowing upward trend from the relatively thin, dark gray mudstone at the base to the overlying thicker, light purplish brown mudstone (Fig. 73). The light purplish brown mudstone represents gradual lowering of relative sea level as the carbonate sediments gradually fill the accommodation space. The

shallowing upward trend resulted from the progradation of the light purplish brown mudstone over the dark gray mudstone. The progradational nature of the light purplish brown mudstone is well documented in the intertonguing of dark gray mudstone with light purplish brown mudstone in the southeast (Fig. 72). The intertonguing and basinward shifting of dark gray mudstone (Fig. 72) are suggestive of a composite parasequence basinward.

Parasequence P6

Parasequence P6 is bounded below by P.B.4 and above by S.B.2 (Figs. 72, 73). The base of P6 is identified by a gradual but rapid increase in bioturbation (Fig. 73). Parasequence P6 consists of a relatively thin, dark gray strongly bioturbated mudstone lithofacies overlain by porous dolostone lithofacies (Figs. 72, 73). Parasequence P6 shows a shallowing upward trend beginning with the dark gray mudstone (Fig. 73). The strongly bioturbated mudstone at the base is analogous to the dark gray, strongly bioturbated mudstone at the base of P5, and is interpreted as deep-water mudstone. The porous dolostone is interpreted to have been deposited in an open marine environment based on the diverse open marine fauna and the sedimentary structures formed by storm processes.

Sequence S3

The sequence S3 is bounded below by the sequence boundary S.B.2 and above by the sequence boundary S.B.3 (Fig. 66). S.B.2 is an erosional unconformity formed on top of sequence S2 with erosional relief of up

to 10's cms (Fig. 20). After deposition of sequence S2 the sea gradually retreated from eastern Wisconsin maybe due to uplift of the Wisconsin. Erosion of the uppermost S2 sequence continued until sequence S3 or S4 began to deposit as the sea gradually transgressed again. Therefore, S.B.2 represents considerable amount of time (Rocklandian; Fig. 67) in eastern Wisconsin particularly where lacks sequence S3 in the north.

S3 consists mostly of thin-bedded skeletal grainstone beds with thin argillaceous partings. They are interpreted to have been deposited in a upper mid-ramp under the influence of frequent storm events. Upward coarsening and decrease in clay content are recognized in this sequence (Fig. 66). A gradual transgression followed by depositional shallowing is observed in the Decorah Formation in southwest Wisconsin by Witzke and Kolata (1989). They suggested that gradual upward decrease in the clay content in the Decorah Formation represents continuous foundering of the siliciclastic source, with the maximum flooding coincident with deposition of the lower Guttenberg Member which is overlain by regressive skeletal wackestone and grainstone to packstone of the upper Guttenberg Member. Sequence S3 only occur south of the Dodge County and pinches out to the north (Appendix C). The pinching out of S3 to the north is interpreted as having been caused by erosion before deposition of sequence S4. The prominent hardground on top of the S3 is interpreted to have formed diachronously during renewed transgression same as the hardground on S.B.1 (Fig. 74).

Sequence S4

Sequence S4 is bounded below by the sequence boundary S.B.2 on top of sequence S2 or by the sequence boundary S.B.3 on top of sequence S3, and is bounded above by the sequence boundary S.B.4 (Appendix C). The S.B.3 is interpreted to be an unconformity based on the following:

- (1) the hardground formed on S.B.3 is widely correlated over much over Wisconsin;
- (2) sequence S3 thins out to the north in the study area, and S.B.3 merges with S.B.2 in north Jefferson County;
- (3) sequence S3 is interpreted to have been deposited in a subtidal zone below FWB but does not have laterally equivalent shallower facies, indicating truncation of this unit;
- (4) the overlying unit, lowermost S4 sequence shows abrupt increase in clay content particularly in the north.

Truncation of the Guttenberg Member (S3) beneath the Dunleith Member (S4) is also reported in eastern Missouri and adjacent Illinois (Kolata et al., 1986, p. 24). Witzke and Kolata (1989) suggested that the area around the Ozark Dome was subaerially exposed at that time. Thus, post-Decorah sea level lowering was probably of interregional scale (Ross and Ross, 1995; Fig. 64). The S.B.4 is an unconformity formed on top of sequence S4. Although the upper contact of sequence S4 is not observed in outcrop, significant erosion before deposition of the overlying Maquoketa Formation is indicated in the cores extracted from southeast Wisconsin by the irregular thickness variation of the uppermost lithostratigraphic unit of sequence S4, the Dubuque Member (Appendix C). The absence of the Dubuque Member in northeastern

Wisconsin also support this conclusion (Moretti, 1971; LoDuca, 1988).

The main lithofacies in sequence S4 are the thin-bedded grainstone (Type 2, 3), shale, porous dolostone, skeletal wackestone to packstone (Type 2), mudstone (Type 3), and crinoidal wackestone lithofacies (Table 9; Fig. 66). The carbonate platform during sequence S4 in eastern Wisconsin seems to have been a ramp with a very gentle slope in a broad open shelf than during the lower sequences based on lack of lateral facies change except the northward increase in clay content over the study area (Appendix C). In general, sequence S4 shows an upward deepening depositional trend with decrease in clay content (Appendix C). Witzke and Kolata (1989) interpreted the gradual upward decrease in the clay content in the Galena Group (corresponds to S3-S4) in Iowa and Illinois to have resulted from marine transgression over the source area, the Transcontinental Arch. Although the upward decrease in clay content fits fairly well with general upward deepening trend in sequence S4, it can also be explained by the gradual change in climate. The climate encompass many factors such as humidity, which controls source area weathering, and amount of fluvial water runoff. These factors controls the siliciclastic input into the depositional site. Therefore, the gradual cooling trend accompanying with aridity during sequence S4 could result in the gradual upward decrease in clay content in sequence S4. Frequent interbedding of argillaceous and carbonate beds may also be explained by climatic change rather than by the sea-level change.

Detailed facies correlation for sequence S4 is very difficult due to lack of continuous outcrop and very gradational vertical changes in

lithology. However, three parasequences are recognized in sequence S4 based on the vertical changes in the identified or inferred textures, clay content, and hardground occurrences (Table 9; Fig. 66).

Parasequence P7

Parasequence P7 is bounded below by the sequence boundary S.B.3 or S.B.2 and above by P.B.5 (Fig. 66). The main lithofacies in P7 are the thin-bedded grainstone (Type 2) and shale lithofacies (Fig. 66). During the deposition of P7, much of eastern Wisconsin was provided with terrigenous clay except the south. The siliciclastics were transported from the north, which is indicated by northward increase in the clay content without change in texture within the same stratigraphic interval. This clay was deposited below FWB and the amount of the input of the clay varied temporally or possibly seasonally. This increased siliciclastic supply resulted in decrease in lime-mud production, which led to more skeletal-dominated composition in the carbonate sediments. Frequent storm events reworked the sediments and transported the skeletal sediments into the upper mid-ramp from the inner ramp. During fair-weather condition, deposition of clay and bioturbation prevailed.

Parasequence P7 shows upward decrease in clay content with accompanying increase in hardground occurrences. This negative correlation is also observed laterally with decrease in clay content to the south with accompanying increase in hardground abundance (Appendix C). This is interpreted as the result of easiness of early cementation of carbonate rocks.

Parasequence P8

Parasequence P8 is bounded above by P.B.5 and below by P.B.6 (Fig. 66). P.B.5 is a sharp to gradational boundary above which there is noticeable decrease in clay content and changes in texture. P.B.6 is a gradational boundary, and corresponds to the top of the upper Dunleith sub-member above which hardgrounds are scarce. Parasequence P8 consists of the porous dolostone, skeletal wackestone, mudstone, and thin-bedded grainstone lithofacies. A general lower mid-ramp setting is interpreted for this parasequence. P8 shows transitional phase from the siliciclastic-dominated setting of P7 to carbonate-dominated setting of P9, which is indicated by abundant interbedding of the argillaceous beds and carbonate beds. It generally shows a shallowing upward depositional succession with upward increase in grainstone beds (Fig. 66).

P8 is characterized by numerous, repetitive hardgrounds (Fig. 66). It is speculated that the particular abundance of hardgrounds in sequence S4 is related to general cooling trend in late Ordovician. The origin of the hardgrounds is discussed in Chapter VI.

Parasequence P9

The parasequence P9 is bounded below by P.B.6 and above by P.B.7 (Fig. 66). P.B.6 is a gradational boundary above which hardgrounds are scarce and is characterized by mudstone lithofacies. The main lithofacies in this parasequence are the mudstone, skeletal wackestone to packstone, and porous dolostone lithofacies. A lower mid-ramp

setting is interpreted for the deposition of parasequence P9.

Parasequence P9 is carbonate-dominated and generally shows a shallowing upward depositional succession with upward increase in grainstone beds (Fig. 66).

Parasequence P10

The parasequence P10 is bounded below by P.B.7 and above by the sequence boundary S.B.4 (Fig. 66). The lithological change from parasequence P9 to parasequence P10 is gradual so identification of P.B.7 is mainly based on the hardground occurrences as well as texture. The main lithofacies in this parasequence are the skeletal wackestone, mudstone, and crinoidal wackestone lithofacies. A lower mid-ramp setting is interpreted for the deposition of parasequence P9.

P10 shows a shallowing upward sequence from mudstone-dominated base to crinoidal wackestone-dominated top. There is a general upward increase in dark brown shaly partings and it may indicate an increase in clastic influx before truncation of the succession.

Summary

After long span of exposure of the entire north American craton, deposition of sequence S1 represents transition from eolian to marine siliciclastic sediments of St. Peter Formation to marine carbonate deposits of Platteville Formation. Sequence S1 shows basal transgressive deposits followed by shallowing upward succession, in which the maximum marine flooding is represented by the deposition of

the shale lithofacies in P2. Parasequence P1 represents initial transgressive deposits of sequence S1 and filled the topography formed on top of Prairie du Chien Group. P2 represents initiation of carbonate deposition and shows landward stepping geometry. P3 records a main phase of carbonate deposition shutting off siliciclastic input in eastern Wisconsin and shows seaward stepping succession. The strata above P3 found elsewhere are missing in eastern Wisconsin. This is interpreted as the result of non-deposition and/or at least partly by the erosion during S.B.1 before the deposition of the overlying strata.

After formation of S.B.1, marine condition transgressed again over the Wisconsin Arch. The rapid transgression resulted in the development of the widespread hardground on the unconformity surface. The depositional sequence S2 shows a general shallowing upward trend. P4 shows onlapping relationship onto the S.B.1, thinning out to the north. P5 and P6 show relatively constant thickness but gradual thinning of P6 is inferred based on the northward truncation of uppermost strata of P6.

After deposition of sequence S2 the sea gradually retreated from the eastern Wisconsin and formed the sequence boundary S.B.2. The unconformity was enhanced by the uplift of the Wisconsin Arch. The prominent hardground on S.B.2 is widely correlated over much of the Midwest, and it is interpreted to have formed during transgressive period after erosion of the uppermost S2 sequence. Sequence S3 onlaps to the north.

A relatively short duration of regression is inferred after deposition of sequence S3 with formation of S.B.3. Sequence S4 shows a

overall deepening upward succession. S4 show gradual upward transition from siliciclastic-dominated settings to carbonate-dominated settings. P7 to P9 show almost constant thickness over the study area. The thickness change in P10 is interpreted as due to erosion before deposition of the Maquoketa Formation.

Each sequence shows gradual transition from a basal siliciclastic-dominated setting to an upper carbonate-dominated setting. The strata above the sequence boundaries are always characterized by relatively high amount of siliciclastic sediments. This correspondence may be related to long-term changes in accommodation space in which periodic lowering of relative sea level controlled siliciclastic supply. However, the relation of the relative sea-level fluctuation with eustasy is not clear although the sequence boundaries are correlated over much of the north American continent. Tectonic pulses related to Taconic Orogeny were probably also involved in the sea-level fluctuation.

S1-S3 sequences show shallowing upward succession with or without basal transgressive deposits. Overall deepening upward trend in sequence S4 is probably due to low carbonate production rate related to the general cooling trend during sequence S4. The gradual upward decrease in clay content in sequence S4 is also explained by gradual decrease in intensity of source area weathering in cooler climate which controls terrigenous clay input. The changes in the clay content observed in smaller scales such as parasequences and beds seem to be better explained with changing climate controlling terrigenous influx than with cyclic changes in relative sea level. Therefore, changes in

climate as well as long-term changes in accommodation space probably had important role in the siliciclastic supply.

One of main characteristics of sequence S4 is the numerous hardgrounds. The particular abundance of hardgrounds in the Galena Formation is probably related to the general cooling trend in late Ordovician. The dominant skeletal lithology, fauna, and lack of composite grains and reef structure in the Galena Formation also support probable temperate climate in Galena time. The paleoclimate and the origin of the hardgrounds in relation to Milankovitch cycle are discussed next and requires further study for verification.

VI. FURTHER STUDY

This thesis concentrated mainly on description and interpretation of the Sinnipee Group in terms of stratigraphic recognition and sedimentologic interpretation. Special emphasis is in the sequence framework and the interpretation in terms of variations in accommodation space, sediment supply, and tectonics. There are several research areas of interest in the Sinnipee Group, which requires further study: the climate of the Caradocian Age, which greatly influenced the deposition of the Sinnipee Group carbonates, and the origin of the abundant ferruginous hardgrounds developed in the Sinnipee Group. These research problems seem to be closely related with each other as well as to the stratigraphic evolution. Outline of current research problems in the Sinnipee Group, preliminary description, and interpretation are summarized next.

1. LATE ORDOVICIAN (GLOBAL STANDARD) CLIMATE

Introduction

There is a common agreement among researchers on a glaciation in the latest Ordovician (late Ashgillian), but there has been much controversy on the timing and duration. Paleoclimate work in the Ordovician has concentrated in the distribution and advance of glacial deposits and variation in fauna, and in stable isotopic data.

Through the Phanerozoic time, long term secular climatic changes are recognized. These secular changes are thought to be caused by

changing CO₂ content of atmosphere in relation to tectonic activity. Although the carbon cycle may be the most important factor responsible for the long-term evolution of climate in the Phanerozoic, regional and seasonal changes in climate related to internal distribution and storage as a result of, e.g., oceanic circulation, changes in land-sea distribution, opening and closing of ocean gateways, etc., also important in climate changes during the Phanerozoic (Frakes et al., 1992). Most early Paleozoic glaciations appear to have occurred in response to movement of continents over the pole (Frakes et al., 1992). Paleomagnetic and biogeographic study reveals that the southern pole was centered on N. Africa during the Late Ordovician which could have potential for continental glaciation (Scotese et al., 1979; Van der Voo, 1988).

Phanerozoic climate is divided into greenhouse periods which are characterized by generally higher CO₂ levels and warmer climate, and icehouse periods characterized by the presence of major continental glaciers and steep latitudinal temperature gradient (Fischer and Authur, 1977). Fischer (1981) assigned a global greenhouse period to the time from Late Cambrian to Early Carboniferous considering the Late Ordovician glaciation to be a relatively short icehouse period. Hambrey (1985) suggested that the glaciation spanned only 1 to 2 m.y. in the latest Ordovician (late Ashgillian) based on the paleontological and sea-level evidence. McKerrow (1979) draw attention to depth-related brachiopod-dominated benthic communities indicative of sea-level change, and collected data from several stable continents. He suggested that a eustatic sea-level fall, spanning less than 1-3 m.y.,

occurred and related it to the ice cap in Gondwanaland. Dark organic-rich shales are a prominent feature of early Paleozoic sedimentation and appear to coincide with warm Phanerozoic climates (Fisher and Arthur, 1977). The concentration of abundant black shales in European sequences is delineated as being in the Caradocian Age (Leggett *et al*, 1981; Thickpenny and Leggett, 1987).

However, Frakes *et al.* (1992) considered a much longer cool climatic mode lasting about 35 m.y. starting in the Caradocian, intensifying in the Ashgillian (latest Ordovician), and waning in the Wenlockian (Early Silurian). The evidence for continental glaciation starting in the Caradocian is that Caradocian marine fossils have been reported from low levels in the glacial sequence in N. Africa (Hambrey, 1985). They also noted that correlation of organic shales with climates is not satisfactory on a fine scale, although many times of extensive organic shale accumulation appear to coincide with warm Phanerozoic climates.

Brass *et al.* (1982) presented stable isotopic data indicating that oceanic bottom water was much warmer in the geological past. They suggested that changes in the size and configuration of marginal seas in net evaporation zones due to plate motions and eustatic sea level change caused these seas to become sources of warm saline bottom water (WSBW). They also interpreted the abundant occurrence of ancient black shales as being the result of WSBW illustrating that the increased temperature of WSBW at its source would reduce concentration of dissolved gases in the source water.

Brenchley *et al.* (1994) used oxygen and carbon stable isotopes to

suggest that major glaciation in the Late Ordovician should be confined to the late Ashgillian (latest Ordovician), spanning 0.5-1 m.y.. They also disputed Frakes et al's (1992) timing of glaciation using Spjeldnaes' (1981) work in which he interpreted the faunas reported from the glacial sequence in Saharan Africa as being in clasts derived from the pre-glacial sequence. Their work illustrates that the Caradocian ocean seem to have been warm.

Preliminary Results and Discussion

Data gathered from the Caradocian Sinnipee Group carbonate indicate that these rock units must have been deposited in a temperate sea, although they were deposited within the equatorial belt (Fig. 3).

The criteria indicating cool-water temperature are as follows:

- 1) The fauna is restricted to brachiopods, bryozoans, crinoids, trilobites, and mollusks
- 2) Reef structure are absent despite the common reef-forming organisms in Late Ordovician (James and Bourque, 1992)
- 3) Non-skeletal grains such as ooids and pellets are absent to rare.

In the Platteville Formation, however, peloid-like grains are observed although their identity are not certain due to dolomitization.

The criteria listed above are characteristics of cool water carbonates (Nelson et al., 1982; James, 1990). Carannante et al. (1988) studied major skeletal components in Recent and Miocene carbonates and distinguished four types of carbonate lithofacies the distribution of which is primarily related to latitude and depth which control water

LITHOFACIES		KEY ELEMENTS	CONSTITUENTS	ENVIRONMENTS
Lees and Buller (1972)	Carannante et al. (1988)	Chlorophyta+ Zoantharia	green algae and hermatypic corals with large benthic foraminifers, branching red algae, molluscs, etc., associated with non-skeletal grains.	tropical rimmed and open shelves
Chlorozoan	Chlorozoan			
Chloralgal	Chloralgal	Chlorophyta	green algae with large benthic foraminifers, branching red algae, molluscs, etc.	transitional and/or anomalous open shelves
Foramol	Rhodalgai	Rhodophyta	encrusting red algae and bryozoans with molluscs, serpulids, etc.	
		Molechfor	molluscs, echinoids, benthic arenaceous foraminifers, barnacles, serpulids, etc.	cold-temperate open shelves

Table 10. Correlation between lithofacies, constituents and carbonate environments (modified from Carannante et al., 1988).

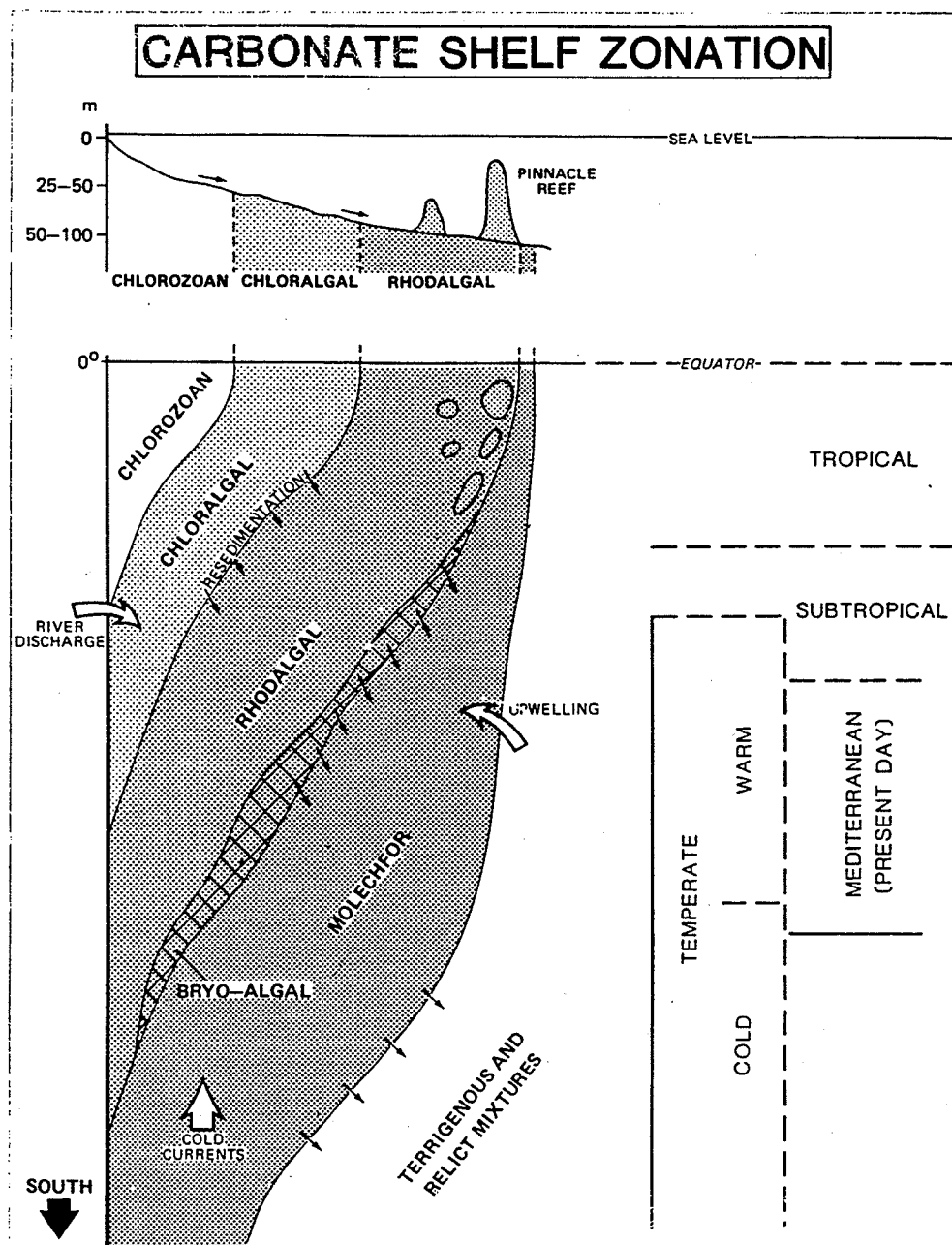


Fig. 75. General carbonate lithofacies model showing trends in the distribution of chlorozoan, chloralgal, rhodalgal and molechfor sediments, according to variations in latitude, water depth and other environmental factors (e.g., upwelling, currents, river discharge). From Carannante et al. (1988).

temperature (Table 10; Fig. 75). According to their classification the dominant faunal associations in the Sinnipee Group (bryozoans, echinoderms, mollusks and lack of green algae) correspond to Rhodalgal to Molechfor facies (Table 10), although the biota such as foraminifers, barnacles, serpulids, and red algae was absent to rare during Paleozoic. However, other factors such as cold water upwelling, river discharge, suspended sediments, and substrate also play a fundamental role on the distribution of the four types of lithofacies (Carannante et al., 1988).

In the Sinnipee Group, there are some indirect evidences implying that there has been composited-eustasy during deposition. The following stratigraphic record might be related to the Milankovitch frequency band:

- 1) Decimeter- to meter-scale cyclic changes in clay content are shown particularly well in the middle Galena Formation.
- 2) Repetitive occurrences of hardgrounds in 5-20 cm intervals in the Galena Formation are frequent and fall within the Milankovitch band (Byers and Geary, 1993).

Therefore, it appears to be a discrepancy between the rock data from the Galena Formation (cool ocean waters, high-frequency cyclicity) and the paleogeographic data (warm oceans, no icecaps). Railsback et al. (1990) applied Brass et al.'s (1982) idea and presented interesting stable isotope model of the Late Ordovician ocean. Railsback et al. (1990) indicate that the Ordovician near-surface or intermediate waters had relatively low temperatures (13-19°C) and low salinities whereas deeper waters were warmer and more saline (28-38°C). They suggested that both the water temperature and

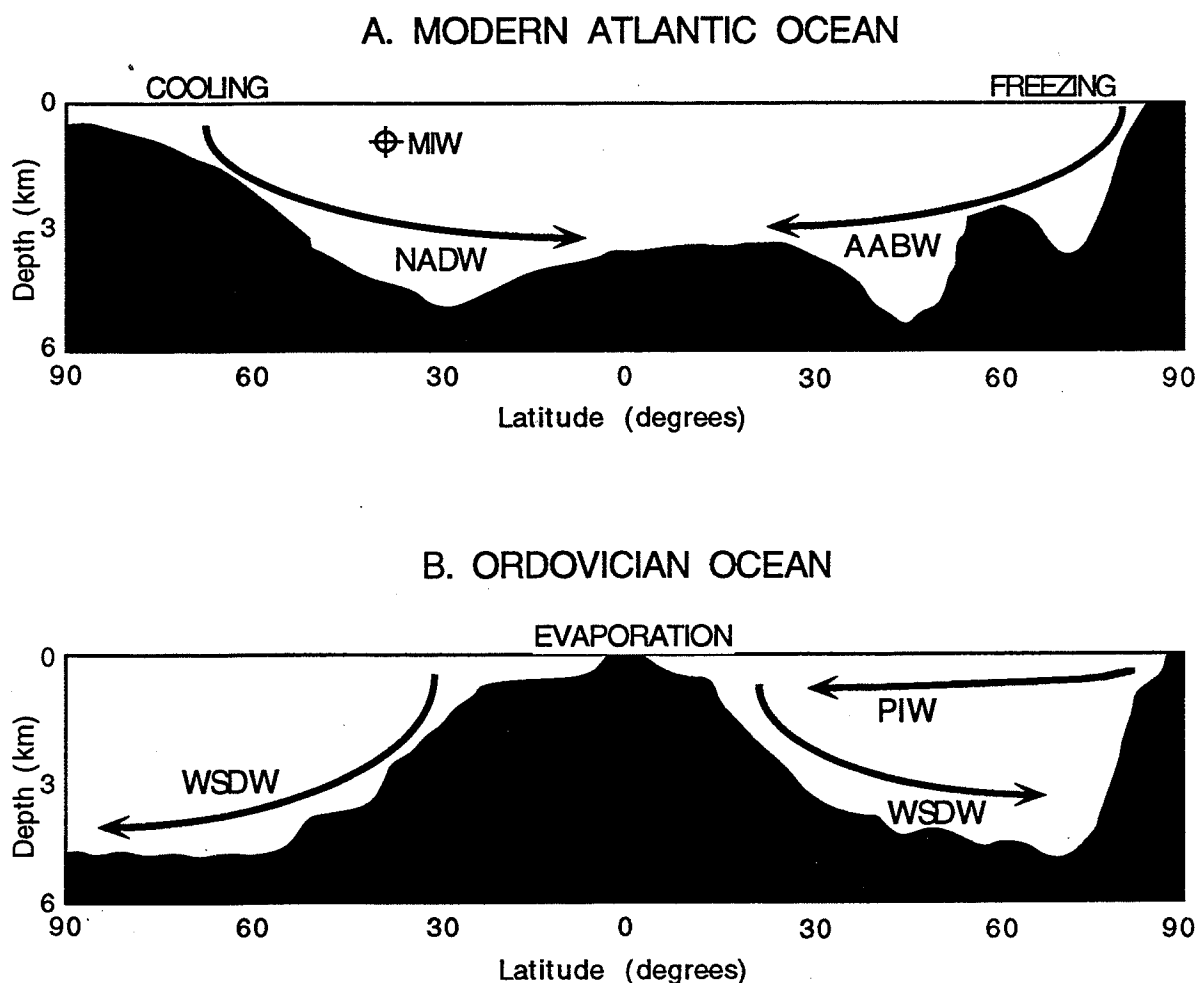


Fig. 76. A. Schematic north-south cross-section of modern Atlantic Ocean showing circulation of major deep water masses. Cold water masses (North Atlantic deep water, NADW and Antarctic bottom water, AABW) form at high latitudes and sink to dominate deep oceans: minor saline water mass (Mediterranean intermediate water, MIW) forms at low latitudes. B. Hypothesized circulation in Ordovician oceans. Warm saline deep water masses (WSDW) formed at low latitudes and sank to dominate deep oceans; minor cold water masses (that is, polar intermediate water, PIW) formed at high latitudes. Therefore, the oceans were salinity stratified with increasing water temperature as water depth increased. From Pailsback et al., 1990.

salinities increased with depth (Fig. 76) and that circulation of cool, polar waters onto the North American craton may also explain the 'temperate appearance of Caradocian faunas', despite their deposition in a tropical paleogeographic setting.

Taking in consideration all the studies listed above and the data from the Platteville and Galena formations, it is suggested that in the Caradocian, the influence of cool waters from the southern pole, on the shallow water temperature in low latitudes increased. The early Caradocian Platteville Formation (Blackriveran Stage, Fig. 2) seems to have been under warmer waters than the late Caradocian Galena Formation. Although the dominant faunal characteristics of the Platteville Formation are similar to those of the Galena Formation above, the relatively abundant micrite and pelletal composition of the Platteville Formation suggest that temperate-water interpretation of the Blackriveran-aged strata located in low latitudes is equivocal (e.g., Brookfield, 1988). The dominant micritic and pelletal composition of the Platteville and equivalent strata is reported in Minnesota (Mossler, 1985), Indiana (Wilcer, 1989), and Ohio (Stith, 1989). Bakush (1985) reported occurrence of peloids in the Galena Group in the Upper Mississippi Valley although the identity of the peloids as true pellets is equivocal.

Lavoie (1995) reported a temperate-water carbonate ramp in Canada which was located in the same latitude and have same age as the Galena Formation in Wisconsin. He suggested that the temperate-water carbonate deposition occurred in spite of low latitudinal setting in the late Caradocian is due to the contraction of warm water belt

resulting in increased input of cold oceanic currents from the southern pole. He also disputed Brookfield's (1988) temperate-water interpretation of the Blackriveran-aged strata. Whether the cause of cold water influence is the contraction of the warm water belt at the equator or southward movement of the continents, the late Caradocian carbonate sediments seem to have been deposited in a temperate water environments unless there were other factors such as cold water upwelling, reduced salinity, increased siliciclastic inputs that could cause shallow-water low-latitudinal carbonate sediments to resemble the physical and faunal characteristics of mid-latitudinal carbonates.

Summary

The late Caradocian sea in North American craton is inferred to have been salinity stratified and characterized by temperate shallow waters resulting in deposition of skeletal carbonates of cool water fauna and by warm deeper waters resulting in black shale deposition in the basin. The Galena Formation, which correspond to the late Caradocian Age, shows the typical characteristics of a temperate carbonate mentioned above. However, general warmer conditions are inferred to have prevailed during deposition of the Platteville Formation. Therefore, although major glaciation during the Late Ordovician should be confined to the late Ashgillian Age as indicated by isotopic studies, general cooling trend is interpreted to have existed during deposition of the Sinnipee Group. The previously mentioned debate among the researchers on the timing of the Late Ordovician glaciation could be matter of, at least partly, size of glaciers existed

during Caradocian.

Methodology

Simple analogy with present temperate ocean only based on faunal assemblage in phylum level is controversial because the dominant biota of the Paleozoic ocean in subtidal environments were similar to the assemblage of present cool ocean. Therefore, close comparison with other areas in different paleolatitude in the Caradocian Age is necessary to support the conclusion. Stable isotope study in the undolomitized area will be also good supporting evidence.

The particular abundance of hardgrounds in the Galena Formation is interpreted to be related to climate, although various factors such as sea-level fluctuation, siliciclastic supply, and other physical, chemical changes in the depositional environment controlling sedimentation rate and early cementation are related to hardground development. Detailed stratigraphic measuring of hardgrounds and analysis of the data to filter out other factors will show the possible relationship of the hardground occurrence and climate.

2. ORIGIN OF HARDGROUNDS

Introduction

Hardgrounds are symsedimentary lithified sea floors (Dathe, 1987). The term 'hardground' is widely used for horizons in marine limestones which show evidence of exposure on the sea floor as lithified rock (Kennedy and Garrison, 1975). They are the result of a

process (early cement precipitation) which occurs when a number of physical and chemical requirements, such as stable grain to grain contacts and a continuing supply of dissolved cement, are satisfied. Once a seafloor has been partially or completely lithified, it may be subject to physical, chemical, and biological erosion. Depending on the types of erosion, Dathe (1987) distinguished two types of hardgrounds:

- 1) Abraded surfaces: surfaces in which some sediment was removed (eroded) by traction-current loads.
- 2) Corrosion surfaces: surfaces in which chemical corrosion of the surfaces was the dominant process.

Previous work in Recent and ancient sedimentary sequences has demonstrated that hardground or potential hardground formation can occur over a wide range of depths and latitudes (Purser, 1969; Kennedy and Garrison, 1975; Brett and Brookfield, 1984; James and Bone, 1994).

Hardgrounds are globally abundant in the Middle to Late Ordovician, possibly because of peculiarities of ocean-water chemistry, coupled with still relatively minor bioturbation of sediments (Wilkinson et al., 1982). Thus the Middle Ordovician carbonate strata containing hardgrounds are studied and reported by many authors (Prokopovich, 1955; Palmer, 1982; Wilkinson et al., 1982; Delgado, 1983a; Brett and Brookfield, 1984). While most of authors related the early cemented nature of those hardgrounds to relative sea level change (Prokopovich, 1955; Wilkinson et al., 1982; Byers and Geary, 1993), Brett and Brookfield (1984) suggested that they are not obviously related with sea level changes, noting the rapidly developed nature of the hardgrounds.

One of the most interesting characteristics of the Middle Ordovician Sinnipee Group is numerous, repetitive occurrences of Fe-mineralized hardgrounds particularly in the Galena Formation. Since the primary work on the hardgrounds by Stauffer (1925), little work has been done to reveal the origin and nature of the hardgrounds occurring in the Sinnipee Group. Prokopovich (1955) worked on the hardgrounds of the Sinnipee Group in Minnesota and suggested that the corrosion zones are developed by non-sedimentation associated to wave action or bottom currents such as turbidity currents. Delgado (1983a) described and interpreted the Galena hardgrounds, and proposed that the hardgrounds in the Galena Formation are not "corrosion surfaces" because the pits and dovetails in the Galena hardgrounds are not the result of chemical erosion, rather they are burrows formed before pre-lithification and borings.

Byers and Geary (1993) proposed a hypothesis that the repetitive occurrences of hardgrounds in the Galena Formation in northern Mississippi Valley are resulted from shoaling events that brought the seafloor within reach of fair-weather wave base, preventing further accumulation of carbonate mud, and cementing the sediment-water interface. They also related the repetitive occurrences of the hardgrounds to the periodicity of Milankovitch cycle, suggesting an estimation of average duration of intervals between hardgrounds of approximately 47,000 years.

Description of the Hardgrounds

Numerous hardgrounds are observed in the Sinnipee Group and they

are particularly abundant in the Galena Formation (Fig. 23). The early cemented nature of the hardgrounds is evident by the common occurrence of 1-2 mm-wide borings on top of hardground surfaces. (Fig. 77). The hardground surfaces are brownish red on weathered surfaces while black on fresh outcrop. The black staining is due to pyrite which is oxidized to hematite and limonite to produce brownish red color on weathered surfaces (Fig. 77). Most of the hardgrounds are prominent with iron-mineral staining, but some of them are easily overlooked due to lack of or obscure staining. There is a complete spectrum of hardgrounds in terms of the prominence. Some hardgrounds are encrusted with very thin (0.1-0.3 mm) phosphorite layers which generally occupy the outmost zone of the hardground (Fig. 78). Pyrite crystals are disseminated with gradually decreasing concentration from the hardground surfaces downward into the sediments and upward into the phosphorite layers (Fig. 78). The pyrite crystals are 0.01-0.1 mm in size and shows euhedral to subhedral shapes (Fig. 78). Sometimes, terrigenous silts are concentrated at the hardground surfaces.

Almost all of the hardgrounds surfaces are irregular with 1-3 cm relief due to bioturbation by *Thalassinoides* burrows, which formed before the hardground development. Even when the other parts of the strata containing hardgrounds lack *Thalassinoides* burrows, they always appear on the hardgrounds. The *Thalassinoides* burrows are 1-2 cm in diameter, showing irregular surfaces. Some hardground surfaces are flat but truncation of the *Thalassinoides* burrows are not clear due to dolomitization. The inside of the burrows are filled with overlying



Fig. 77. Plain view of the hardground on top of the Platteville Formation showing the hardground stained by pyrite and oxidized products of the pyrite - hematite and limonite. Note 1-3 mm-wide borings. Coin for scale is 2.5 cm long. Watertown Qr., Locality 2.

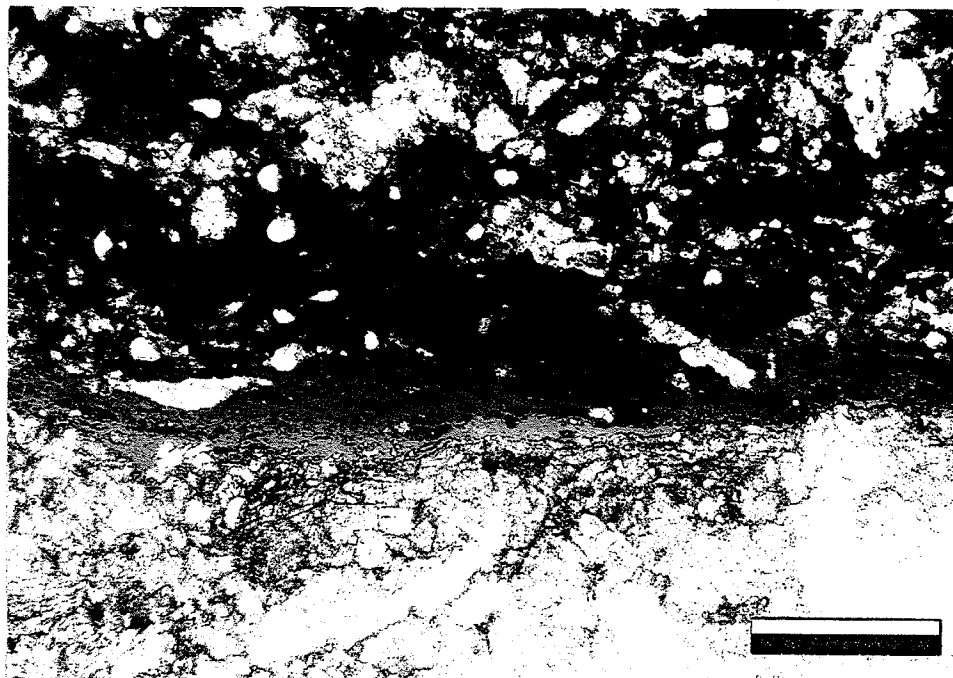


Fig. 78. Photomicrograph of a hardground showing pyrite (black) and phosphorite (yellow). The Photo was taken from the roof of a *Thalassinoides* burrow. The lower portion composed of dolomite is inside of the burrow. This indicate that the phosphorite layers were precipitated, not deposited. Scale bar is 0.5 mm long. From the uppermost GAL 1. Locality RA [U.W.1896/24].

sediments. The burrow walls are also stained dark due to mineralization of pyrite and phosphorite (Fig. 78).

In general, most of the hardgrounds are developed on bioclastic wackestone to grainstones, but hardgrounds formed on mudstones are not uncommon. Overlying the hardground surfaces are generally finer grained mudstone to wackestones, however, grainstones with black pebbles floating in a bioclastic calcarenite matrix are not uncommon. The black pebbles are thought to have derived from the underlying hardground. Interestingly, many of the bioclasts of sand size are also stained by pyrite, which results in the appearance of black spots in the grainstone beds.

Description of faunal communities on the hardground surfaces are not established due to scarceness of exposed bedding plains on which the hardgrounds developed. However, abundant crinoids and bryozoans are observed attached to the hardground surface on top of the Platteville Formation.

The hardgrounds are laterally extensive at outcrop scale, but the use as a tool in regional correlation of individual hardgrounds is doubtful except some prominent hardgrounds which bound lithologic units including members and formations. Correlation between outcrops of hardground bundles is fairly useful, however. (Appendix C).

The relative abundance of the hardgrounds in the Sinnipee Group are plotted on a curve to see the relationship with inferred water depth (Fig. 79). Most of the hardgrounds in the Glenwood Member and the Platteville Formation occur on the mudstone to wackestone lithologies and show good correlation with interpreted trends from deeper-water

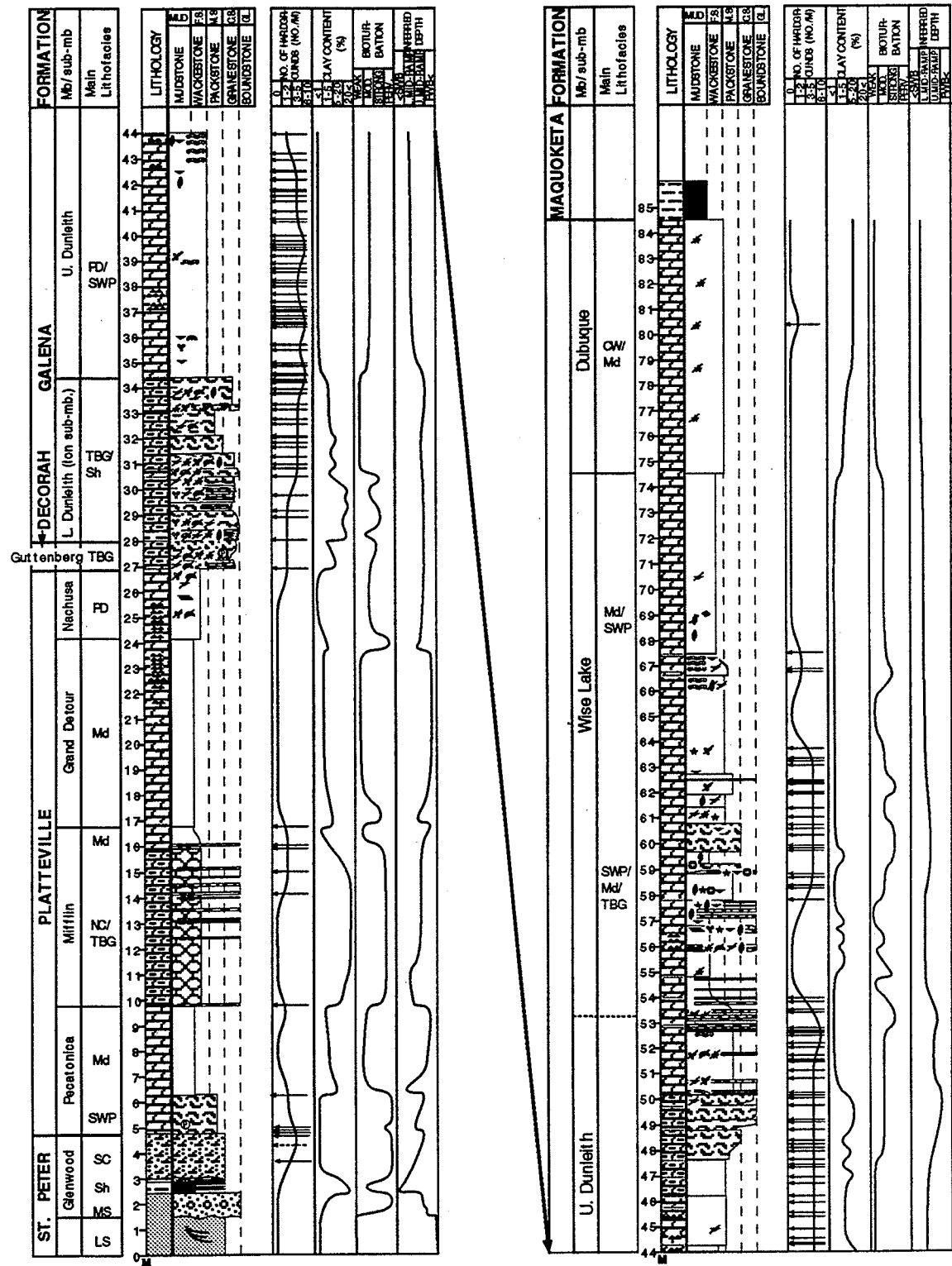


FIG. 79. Composite Section of the Sinnipee Group in E WI., showing curves of hardground abundance, clay content, degree of bioturbation, and relative sea-level. Note general coincidence of the hardground abundance curve and the relative sea-level curve in the Platteville Formation except in the lagoonal mudstone (Pecatonica and Grand Detour members). In the Galena Formation, they occur indiscriminately on wackestone to grainstone but not in mudstone. Key in Fig. B-1, 2.

to shallow-water facies (Fig. 79). The Galena hardgrounds occur much more frequently than in the Platteville Formation and indiscriminately on wackestone to grainstone lithologies. The thickness of sediments between hardgrounds in the Galena Formation ranges 3-50 cm, most of them 5-20 cm in the zones of abundant hardgrounds (Fig. 80, HB). Figure 80 shows a Fischer plot of the Sinnipee Group hardgrounds. Closely spaced hardgrounds form steep areas (HB1-9). It shows that hardgrounds are more frequent in the lower part of each sequence than the upper part. Figure 81 compares the Sinnipee Group hardgrounds with clay content, bioturbation, and storm bed abundance. Hardground abundance is negatively correlated to clay content the hardgrounds being more abundant in the intervals of argillaceous-free lithology, particularly in the Galena Formation. Degree of bioturbation in Fig. 81 does not show correlative relationship with hardgrounds, but the occurrence of *Thalassinoides* burrows in every individual hardgrounds indicate strong positive correlation with bioturbation by *Thalassinoides*. However, abundant *Thalassinoides* bioturbation throughout P9 suggests that the positive correlation could be attributed to the easier recognition of the *Thalassinoides* burrows at the hardgrounds due to pyrite staining. Individual storm beds does not show any direct correlation to hardground occurrences (Fig. 81). The occurrence of receptaculites shows a strong negative correlation to the hardground frequency (Fig. 81). This indicate the possible climate control on the hardground development because receptaculites occurrence represents warmer climate (Nitecki, 1972).

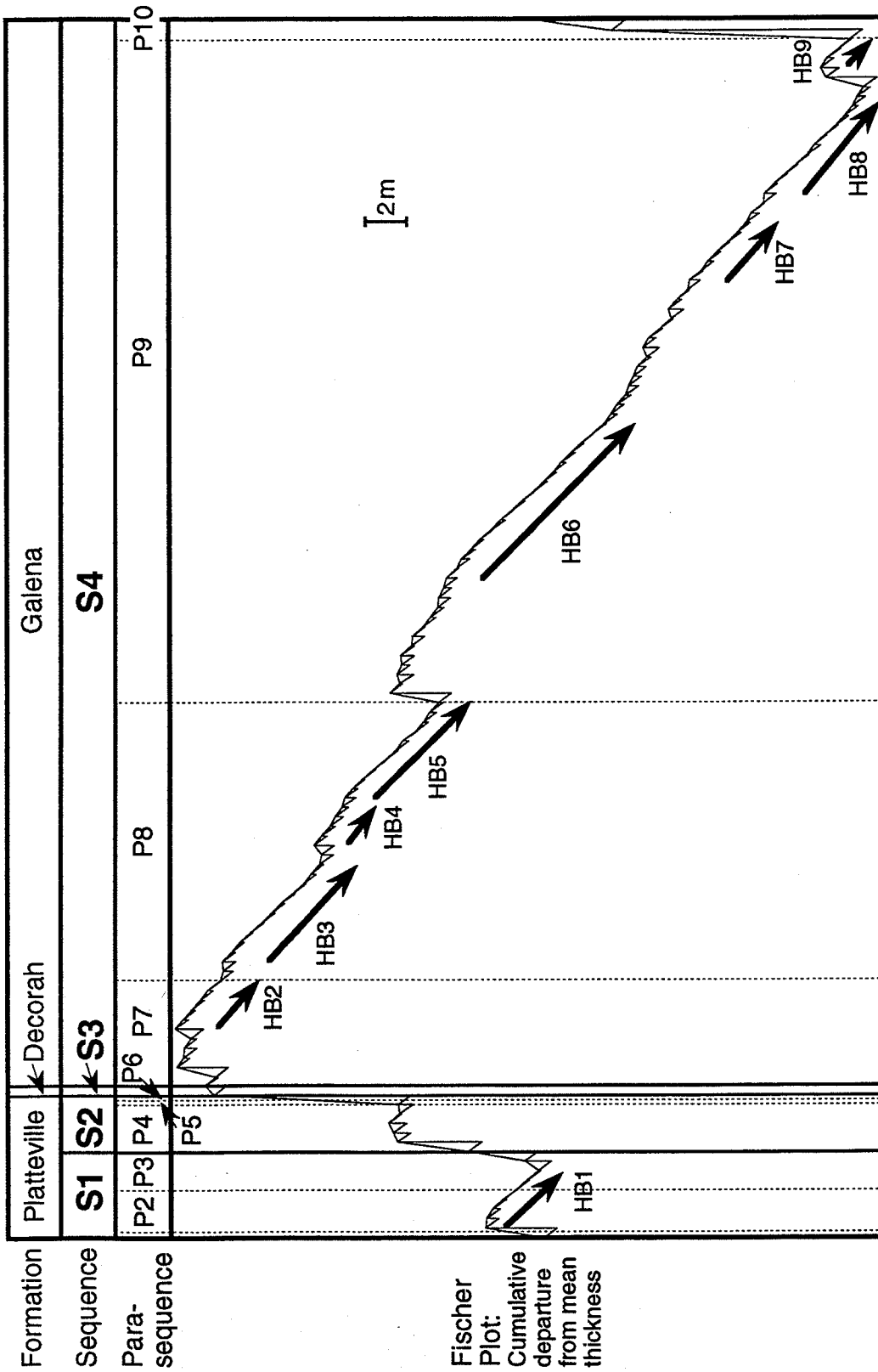


Fig. 80. Fischer plot of the Sinipee Group hardgrounds. Stratigraphy for S1 and S2 comes from several sections and S3 is from Locality 1, and for S4 from Locality JE. Bold arrows represent intervals of abundant hardgrounds (HB: hardground bundle). This diagram shows that the hardgrounds are more frequent in the lower part of each sequence than the upper part.

Fischer Plot:
Cumulative departure from mean thickness

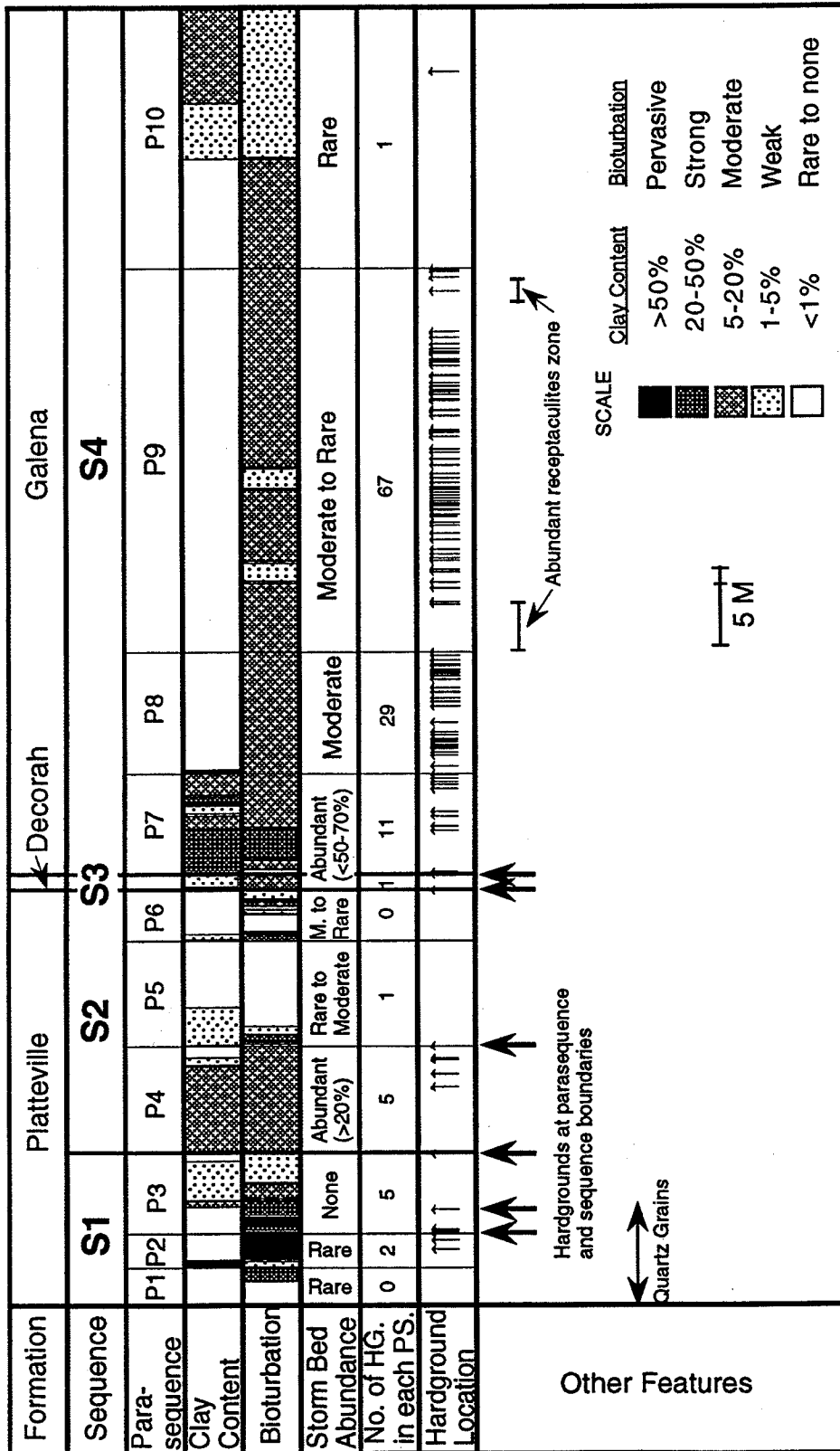


Fig. 81. Columnar section of the Sinipee Group comparing hardgrounds with clay content, bioturbation and storm bed abundance. Stratigraphy for S1 and S2 comes from several sections or S3 is from Locality 1, and for S4 from Locality JE. This diagram shows that the hardgrounds are more frequent in the parasequence boundaries and the lower part of each sequence. Note the negative correlation of hardground frequency and the receptaculites zone.

Preliminary Interpretation and Discussion

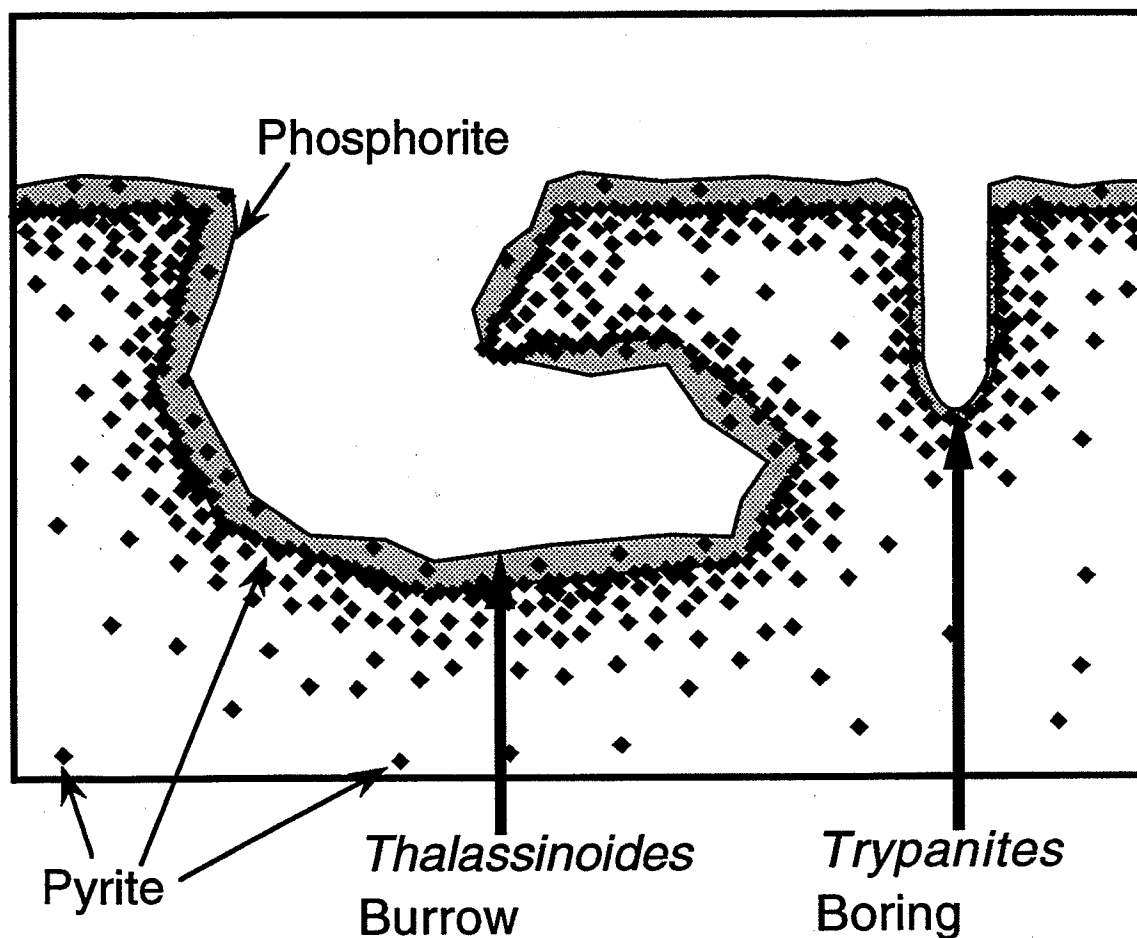
Paragenesis of the hardground formation

The sequence of events related to the hardground formation and associated minerals are established as follows:

- (1) *Thalassinoides* burrowing on the stable substrate, just before early cementation during initial stage of non-depositional period
- (2) Non-deposition and early marine cementation
- (3) Borings on consolidated substrate
- (4) Phosphorite precipitation
- (5) Pyrite mineralization in burial.

Figure 82 shows the minerals associated with the hardgrounds and the paragenetic relationship among them. During initial stage of non-depositional time, the sediments became coherent and the 1-2 cm-wide *Thalassinoides* burrowing prevailed mostly within the upper 10 cm near the sediment-water interface. Unlike the mm-sized *Chondrites* burrows, which are abundant throughout the Sinnipee Group, the *Thalassinoides* burrows develop on a relatively stable substrates (Frey et al., 1978; Frey and Seilacher, 1980; Sheehan and Schiefelbein, 1984; Bromley and Ekdale, 1984). The restricted occurrence of the *Thalassinoides* burrows to the hardgrounds in most of the Sinnipee Group strata is explained by this interpretation. Following the bioturbation by the *Thalassinoides*, the substrate was cemented and 1-2 mm-wide borings formed.

Although the location of the phosphorite on the outmost surface



PARAGENESIS

1. *Thalassinoides* burrowing
 2. Non-deposition and Early Cementation ←?
 3. *Trypanites* Boring ←?
 4. Phosphorite Precipitation
 5. Pyrite Mineralization during Burial
- Supply of Precursor
of Pyrite

Fig. 82. Schematic diagram showing the occurrence of the minerals associated with hardgrounds. The pyrite crystals are disseminated through the phosphorite layer and sediments with upward and downward decreasing concentration from the hardground surface. The phosphorite layer occupy the outmost zone. However, the euhedral to subhedral shape of the pyrite crystals disseminated through the phosphorite layer indicates that the mineralization of the pyrite postdates the phosphorite precipitation. See text for details.

suggests that it is younger than the pyrite, pyrite replacing textures indicate that the pyrite is the youngest and postdated the phosphorite. It may be that an iron-rich mineral precipitated before the phosphorite as a precursor material and later transformed into pyrite. The processes and timing of the supply of the precursor material of the pyrite can be explained in two ways. The first possible explanation is that Fe ion was supplied from the sea-water during non-depositional time and permeated through the sediments with carbonate-supersaturated sea-water cementing the sediments. The gradual downward decrease in pyrite staining is interpreted to be due to downward decreasing circulation rate of pore water. This explanation can also explain preferential pyrite staining of the Type A bioclasts of which taphonomic features indicate prolonged exposure on the sea floor before burial. However, for this process to take place, a reducing condition should be assumed for Fe ion to substitute Ca ion. Another explanation is that the sea floor was being enriched by organic matter and later by phosphorite with gradually increasing proportion during the non-depositional period after early cementation. The organic-rich sediments led to the formation of pyrite with supply of Fe ion during burial. The problem with this interpretation is that it can not explain the downward decrease in the pyrite staining in the *Thalassinoides* burrows, because the pyrite staining also intense on the roof of the *Thalassinoides* burrows that are close to the hardground surfaces. However supplied the precursor material of the pyrite have been, its texture indicates that the mineralization of the pyrite was latest.

Phosphorites are formed by deposition, precipitation, and replacement (Baturin, 1982). The occurrence of the phosphorite layer on the roof of the burrow (Figs. 78, 82) rule out the possibility of deposition of the phosphorite. The outmost occurrence of the phosphorite also exclude the possibility of replacement of carbonate by the phosphate because phosphatization occurs below sediment-water interface in the interstitial waters rich in dissolved phosphorus rather than in normal sea waters (Baturin, 1982). Whether the supply of the phosphorus from sea water or from the sedimentary layer is not clear. Under oxic conditions phosphate is strongly adsorbed and precipitated with ferric iron oxides. Upon removal of oxygen and subsequent reduction of Fe, phosphate is liberated to solution (Ingall et al., 1993). Thus, phosphorus released in the lower portion of sediments containing organic phosphorus (inarticulate brachiopod fragments) could potentially be precipitated by oxidizing conditions at the sediment-water interface during or after early cementation. Further study on the chemical condition for the precipitation of the phosphorite with other associated minerals is required to decide the timing.

Processes related with hardground formation

Although general characteristics and associated minerals on the Sinnipee Group hardgrounds are similar, more than one process seem to be involved in the formation of individual hardgrounds with varying degrees.

Hardgrounds are formed by early cementation during periods of very slow or non-sedimentation. Prolonged times of non-sedimentation

in carbonate sediments can result from transgression, physical changes (i.e., changes in energy regime), or chemical changes such as salinity and pH, which influence carbonate production. Different mechanisms can count for each of these events. Some hardgrounds are well explained by transgression, some are explained by physical changes in the depositional environment, and some are better explained by environmental changes. All the hardgrounds are associated with pyrite and phosphorite, thus to deposit and/or precipitate these, events of reducing condition, i.e., anoxia, should be assumed at least as one of stages in the events of non-deposition.

The hardgrounds in the Glenwood Member and the Platteville Formation are particularly abundant at the base of the parasequence boundaries, which show evidences of deepening event. Those hardgrounds are interpreted to be related to decreased sedimentation rate during transgressive periods. Hardgrounds are also common in the interpreted shallower-water facies in the Glenwood Member and the Platteville Formation except in the lagoonal mudstone. Those hardgrounds are probably related to wave-inhibition of sedimentation in a open marine setting.

The numerous repetitive occurrence of hardgrounds in the Galena Formation requires more refined interpretation. Chemical controls related with climate change probably had an important role in the formation of the Galena hardgrounds. Several models have been proposed to explain the repetitive nature of the Galena hardgrounds.

Relation with Milankovitch Cycle

Byers and Geary (1993) proposed a hypothesis regarding the possible relationship between the repetitive nature of the Galena hardgrounds and Milankovitch cyclicity. However, simple calculation of the average duration of the cycles to induce Milankovitch cyclicity have problems as follows.

- (1) Amalgamation: there are some amalgamated hardgrounds which are difficult to identify in the field.
- (2) Preservation: not every hardground is preserved as a rock record at every location. There are many grainstone beds which contain some floating dark intraclasts derived from a hardground layer but do not directly overlie any hardground surface, indicating that not all of the hardgrounds were preserved.
- (3) Missed beats: if sea level change is the main control on the hardground formation there should be cycles during which no hardground is formed (Goldhammer et al., 1993).
- (4) In general, there is a tendency to overlook some hardgrounds rather than counting more than truly existed because the prominence of hardgrounds is variable depending on the intensity of early cementation and pyrite mineralization, which makes identification of some hardgrounds ambiguous.

Therefore, comparison of the hardground occurrences with other cyclic signals such as periodic shallowing upward cycles and with lithologies seems to be better approach. Diagenetic study on the pyrite, phosphorite, and carbonate cements on the hardgrounds will be useful

to reveal the sea-water chemistry which influenced the sedimentation of those minerals at the time of hardground formation. To prove cyclicity it is necessary to show periodicity first. However, there could be so many factors which influence sedimentation and make the occurrence of the hardgrounds episodic in the stratigraphic record even if the periodic factor exist. For example, changing sedimentation rate could erase the possible periodic signal of hardground occurrences. Therefore, the periodic signal will only occur in the intervals in which other factors are relatively constant.

There seem to be chemical constraints to control formation of hardgrounds such as sea water chemistry including redox potential and pH as well as physical constraints such as base level change. Periodic change of such constraints could result in repetitive hardgrounds.

Sea-level vs. climate Control

Hardgrounds are often considered to mark the tops of regressive sequences (Kennedy and Garrison, 1975; James and Bone, 1994), followed by a transgression (Purser, 1969). However, many of the Ordovician hardgrounds, which are interpreted to have developed rapidly, are not obviously related with sea level changes (Brett and Brookfield, 1984). Application of only sea level control to explain the formation of the Galena hardgrounds has the following problems.

- (1) In most cases the intervals between hardground surfaces do not show distinct coarsening upward sequence which is expected if periodic reach of the sediment surfaces into the zone of wave influence is the main mechanism of the

hardground development (James and Bone, 1994).

- (2) Considering the good lateral continuity of the hardgrounds particularly in the lower Galena Formation (GAL 2, Appendix C), putting the vast area into the zone of erosion seems unreasonable because wave energy dissipates rapidly when it touches the bottom of the sea unless the hardground surfaces are time transgressive.
- (3) Considering similar physiographic setting and environment, much fewer hardgrounds are developed in the underlying Platteville Formation even on similar lithology.

Therefore other factors are needed to explain the repetitive nature of the hardgrounds. The alternative hypothesis which postulated periodic climate change as a main control on the cyclical hardground formation is suggested in this study.

Alternative hypothesis

Considering the characteristics described previously and the problems of the hypothesis proposed before, it is postulated that the Galena hardgrounds have formed in deeper water, below FWB but above SWB, in relation to Milankovitch induced periodical change of climate which influenced the near-surface water temperature and chemistry as well as sea level.

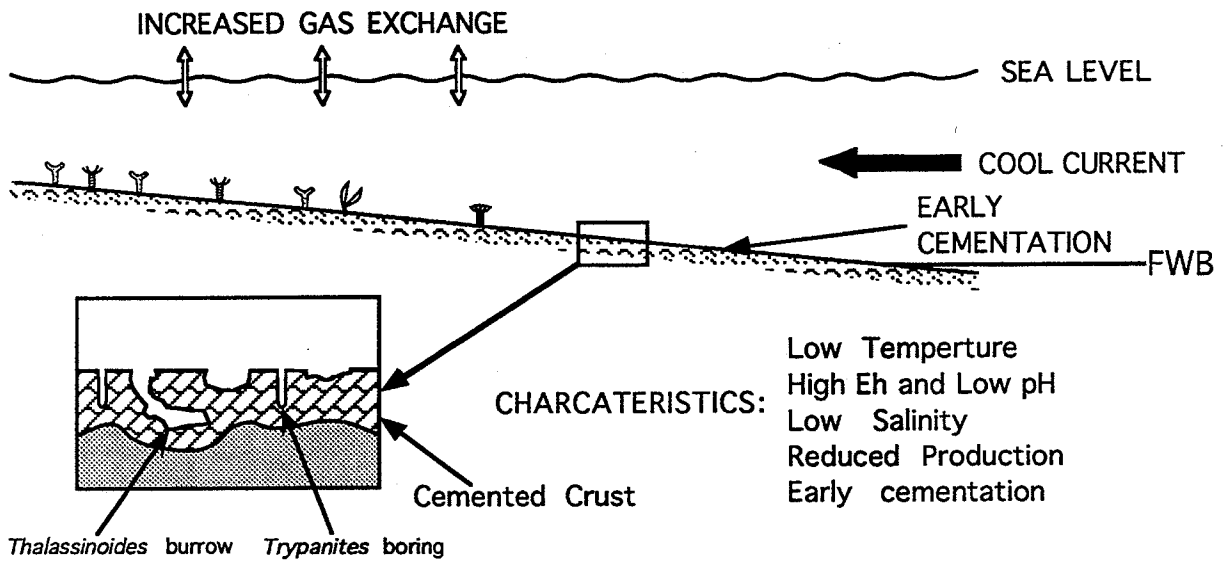
In late Caradocian time, the ocean water was salinity stratified, with increasing temperature with water depth, and near-surface or intermediate water characterized by relatively low temperatures (13-19 °C) and low salinities (26-29 p.p.t.) (Railsback et al., 1990; Fig. 76).

The numerous occurrences of the Galena hardgrounds can be interpreted in relation with the decreased surface ocean temperature during Galena time.

As the glaciation at the southern continents intensified during late Caradocian, the cold water generated from the southern pole periodically reached North American continent as surface water (Fig. 83). The oceans of cooler periods are characterized by (1) increased influence of cool currents from high latitude, (2) increased gas exchange such as O_2 and CO_2 between the atmosphere and sea water due to low temperature, (3) higher Eh and lower pH, (4) decreased water depth, if glaciation existed, (5) low carbonate production rate due to low salinity and water temperature, and (6) early cementation resulting in hardground formation (Fig. 83A).

The warmer periods are characterized by (1) weak or no input of cool currents from the south, (2) decreased gas exchange due to high temperature, (3) lower Eh and higher pH in sea water, (4) increased water depth, (5) increased carbonate production due to higher salinity and water temperature, (6) increased accumulation of organic carbon due to lower Eh which result in phosphorite precipitation (Fig. 83B).

A. Cooler Period



B. Warmer Period

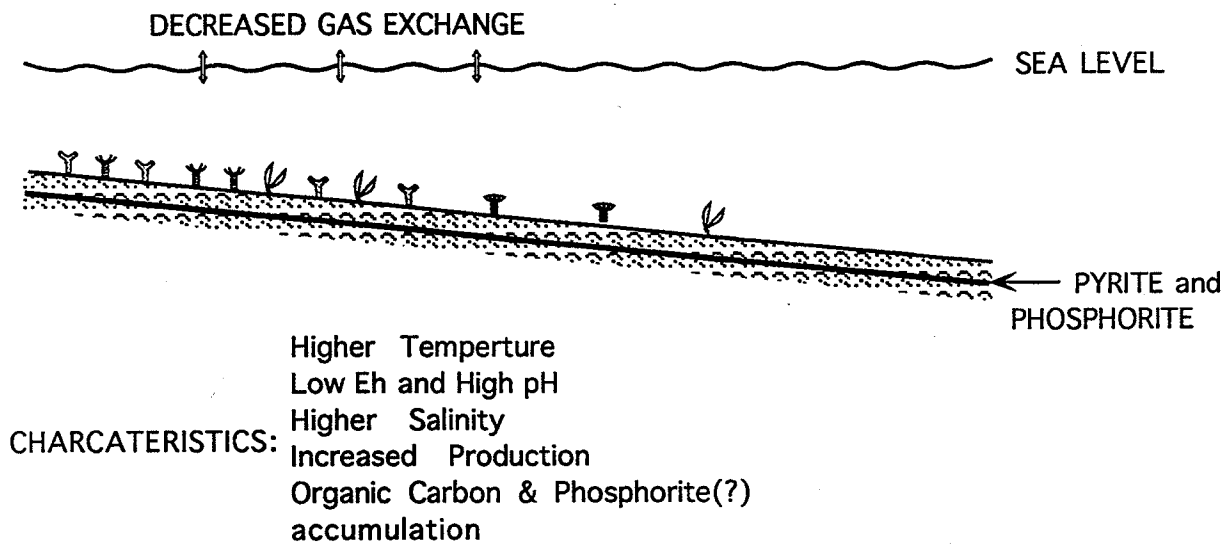


Fig. 83. Schematic diagram illustrating origin of the Galena hardgrounds. Periodic influence of cool current from the southern pole results in widespread hardgrounds development in the late Caradocian sea.

Proposed Work and Methodology

Hardgrounds in recent environments have been described from supratidal, subtidal shelf, slope, and deep-sea environments (Shinn, 1969; Neumann et al., 1979; Dravis, 1981; Mullins et al., 1982). Thus, before the environmental significance of hardgrounds can be evaluated, the environment of deposition of the associated sequences must be established. A statistical approach is needed to document the relationship between hardgrounds and specific lithofacies.

Fluorescence and cathodoluminescence methods are useful to identify the original textures of dolomite and to establish diagenetic history. To accomplish these, field and petrographic study on the Sinnipee Group in undolomitized area will be necessary for correlation.

Petrographic evidences used by many authors will be used to make inferences about the nature and origin of hardgrounds. Of particular importance is the evidence of erosion and scour in the interpretation of paleowater depth. To establish more precise and detailed paragenetic relationship among various fabric elements, diagenetic study on carbonate cements and associated minerals such as pyrite and phosphorite are important. Diagenetic and geochemical study on the associated minerals will also help to reveal the environment of deposition and/or precipitation of them and the relative timing of their formation in the course of the hardground development. Analysis of attached hardground communities should be performed to infer the environmental condition and the nature of the hardgrounds.

To test the cool-water related origin of the Galena hardgrounds, comparison of the occurrences of the hardgrounds with those of

receptaculites seems useful considering warmer temperature required for the 'bloom' of receptaculites. If the relative abundance of the hardgrounds decrease with increase of receptaculites it will be a good supporting evidence.

REFERENCES

- Abed, A.M. and Schneider, W., 1980, A general aspect in the genesis of nodular limestones documented by the Upper Cretaceous limestones of Jordan. *Sed. Geol.*, v. 26, p. 329-335.
- Agnew, A.F. and Heyl, A.V., Behre, C.H., and Lyons, E.J., 1956, Stratigraphy of Middle Ordovician rocks in the zinc-lead district of Wisconsin, Illinois, and Iowa: U.S. Geological Survey Professional Paper 274-k, p. 251-312.
- Agnew, A.F. and Heyl, A.V., 1946, Quimbys Mill, new member of Platteville Formation, Upper Mississippi Valley. *Amer. Assoc. Petrol. Geol. Bull.*, v. 30, p. 1585-1587.
- Ahr, W.M., 1973, The carbonate ramp-an alternative to the shelf model. *Trans. Gulf Coast Assoc. Geol. Soc.*, v. 23, p. 221-225.
- Aigner, T., 1985, Storm depositional systems. Berlin, Springer-Verlag, 174p.
- Atkinson, R.F., 1971, Platteville Formation conodonts, *in* Clark, D.L., Conodonts and biostratigraphy of the Wisconsin Paleozoic. Wisconsin Geological and Natural History Survey Information Circular 19, p. 18-33.
- Bain, H.F., 1905, Zinc and lead deposits of northwestern Illinois. U.S. Geological Survey Bulletin 246.
- Bakush, S.H., 1985, Carbonate microfacies, depositional environments and diagenesis of the Galena Group (Middle Ordovician) along the Mississippi River (Iowa, Wisconsin, Illinois, and Missouri), U.S.A.: [Ph. D. thesis]; University of Illinois at Urbana-Champaign, 223p.
- Bates and Jackson, 1980, Glossary of geology. 2nd edition, Amer. Geol. Ins., Falls Church, Virginia, 751p.
- Baturin, G.N., 1982, Phosphorites on the sea floor: Origin, composition and distribution. *Developments in Sedimentology* 33, 343p. Elsevier.

- Brass, G.W., Southam, J.R. and Peterson, W.H., 1982, Warm saline bottom water in the ancient ocean. *Nature*, v. 296, p. 620-623.
- Braun, M. and Friedman, G.M., 1969, Carbonate lithofacies and environments of the Tribe Hill Formation (Lower Ordovician) of the Mohawk Valley, New York, *Jour. Sed. Petrol.*, v. 39, p. 113-135.
- Brenchley, P.J., Marshall, J.D., Carden, G.A.F., Robertson, D.B.R., Long, D.G.F., Meidla, T., Hints, L., and Anderson, T.F., 1994, Bathymetric and isotopic evidence for a short-lived Late Ordovician glaciation in a greenhouse period. *Geology*, v. 22, p. 295-298.
- Brett, C.E. and Brookfield M. E., 1984, Morphology, faunas and genesis of Ordovician hardgrounds from southern Ontario, Canada. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, v. 46, p. 233-290.
- Brett, C.E. and Baird, G.C., 1986, Comparative taphonomy: a key to paleoenvironmental interpretation based on fossil preservation. *Palaios*, v. 1, p. 207-227.
- Bromley, R.G. and Ekdale, A.A., 1984, *Chondrites*: a trace fossil indicator of anoxia in sediments. *Science*, v. 224, p. 872-874.
- Brookfield, M.E. and Brett, C.E., 1988, Paleoenvironments of the Mid-Ordovician (Upper Caradocian) Trenton limestones of southern Ontario, Canada: Storm sedimentation on a shoal-basin shelf model. *Sed. Geol.*, v. 57, p. 75-105.
- Burchette, T.P. and Wright, V.P., 1992, Carbonate ramp depositional systems. *Sedimentary Geology*, v. 79, p. 3-57.
- Buschbach, T.C., 1964, Cambrian and Ordovician strata of northeastern Illinois: Illinois State Geological Survey Report of Investigation, no. 218, 90 p.
- Byers, C.W., 1983, Platteville stratigraphy and sedimentology *in* Byers, C.W., Delgado, D.J., Dott, R.H., Jr., Pray, L.C., and Winfree, K.E., eds., Guidebook, 17th North-central Section GSA, p. 14-16.

- Byers, C.W. and Geary, D.H., 1993, Milankovitch cyclicity in the Ordovician: Periodic hardground generation in the Galena Group, northern Mississippi Valley. *Abstracts-with-Programs-Geological-Society-of-America*, v. 25, no. 6, p. 338.
- Carannante, G., Esteban, M., Milliman, J.D., and Simone, L., 1988, Carbonate lithofacies as paleolatitude indicators: problems and limitations. *Sed. Geol.*, v. 60, p. 333-346.
- Chamberlain, T.C., 1877, Geology of eastern Wisconsin. *Geology of Wisconsin*, v. 2, p. 336-371.
- Choquette, P.W. and Pray, L.C., 1970, *Amer. Assoc. Petrol. Geol. Bull.*, v. 54, no. 2, p. 207-250.
- Clark, D.L. and Babcock, L.C., 1971a, Decorah Formation conodonts, *in* Clark, D.L., *Conodonts and biostratigraphy of the Wisconsin Paleozoic: Wisconsin Geological and Natural History Survey Information Circular 19*, p. 34-37.
- Clark, D.L. and Babcock, L.C., 1971b, Galena Dolomite conodonts, *in* Clark, D.L., *Conodonts and biostratigraphy of the Wisconsin Paleozoic: Wisconsin Geological and Natural History Survey Information Circular 19*, p. 38-41.
- Cohee, G.V., 1948, Cambrian and Ordovician rocks in Michigan Basin and adjoining areas. *Amer. Assoc. Petrol. Geol. Bull.*, v. 32, p. 1417-1448.
- Cohee, G.V., 1965, Geologic history of the Michigan Basin. *Washington Acad. Sci. Jour.*, v. 55, no. 9, p. 211-223.
- Cook, H.E., and Mullins, H.T., 1983, Basin margin, *in* Scholle, P.A., Bebout, D.G., and Moore, C.H., eds., *Carbonate Depositional Environments*, *Amer. Assoc. Petrol. Geol., Memoir 33*, p. 171-211.
- Dathe, D., 1987, Corrosion surfaces in the Platteville and Galena strata of southeastern Minnesota, *in* Middle and Late Ordovician lithostratigraphy and biostratigraphy of the upper

Mississippi Valley, Sloan, R.E., ed., Minnesota Geological Survey, report of investigation 35, p. 59.

Delgado, D.J., 1983a, Deposition and diagenesis of the Galena Group in the Upper Mississippi Valley, In Delgado, D.J. ed., Ordovician Galena Group of the Upper Mississippi Valley -- Deposition, diagenesis, and paleoecology, Guidebook for the 13th Annual Field Conference, p. A1-17.

Delgado, D.J., 1983b, Road log, Dubuque to Decorah, In Delgado, D.J. ed., Ordovician Galena Group of the Upper Mississippi Valley -- Deposition, diagenesis, and paleoecology, Guidebook for the 13th Annual Field Conference, p. R1-38.

Dott, R.H., Jr. and Prothero, D.R., 1994, Evolution of the Earth, 5th ed., 569p.

Dravis, J., 1979, Rapid and widespread generation of Recent oolitic hardgrounds on high energy Bahaman platform, Eleuthera Bank, Bahamas. Jour. Sed. Petrol., v. 49, p. 195-208.

Droste, J.B. and Shaver, R.H., 1983, Atlas of Early and Middle Paleozoic paleogeography of the Southern Great Lakes Area. Indiana Geological Survey, Special Report 32, 32 p.

Dunham, R.J., 1962, Classification of carbonate rocks according to depositional texture, in Classification of Carbonate Rocks, Ham, W.E., ed., p. 108-121.

Embry, A.F. and Klovan, J.E., 1971, A Late Devonian reef tract on northeastern Banks Island, N.W.T.. Bull. Canadian Petrol. Geol., v. 19, p. 730-781.

Enos, P. and Moore, C.H., 1983, Fore-reef slope, in Scholle, P.A., Bebout, D.G., and Moore, C.H., eds., Carbonate Depositional Environments, Amer. Assoc. Petrol. Geol., Memoir 33, p. 507-537.

Fischer, A.G., 1981, Climatic oscillations in the biosphere, in Biotic crisis in ecological and evolutionary time, Nitecki, M., ed., p.103-131. New York Aca. Press.

- Fischer, A.G. and Arthur, M.A., 1977, Secular variations in the pelagic realm, *in* Deep Water Carbonate Environments, Cook, H.E. and Enos, P., eds., SEPM Special Publication 25, p. 19-50.
- Frakes, L.A., Francis, J.E., and Syktas, J.I., 1992, The cool mode: late Ordovician to early Silurian, *in* Climate modes of the Phanerozoic. p. 15-26.
- Fraser, G.S., 1976, Sedimentology of a Middle Ordovician quartz arenite-carbonate transition in the upper Mississippi Valley. *Geol. Soc. Amer. Bull.*, v. 86, p. 833-845.
- Frey, R.W., Howard, J.D., and Pryor, W.A., 1978, *Ophiomorpha*: its morphologic, taxonomic, and environmental significance. *Palaeogeog., Palaeoclimatol., Palaeoecol.*, v. 23, p. 199-229.
- Frey, R.W. and Seilacher, A., 1980, Uniformity in marine invertebrate ichnology. *Lethaia*, v. 13, p. 183-207.
- Garrison, R.E. and Kennedy, W.J., 1977, Origin of solution seams and flaser structure in Upper Cretaceous Chalks of southern England. *Sed. Geol.*, v. 19, p. 107-137.
- Goldhammer, R.K., Lehmann, P.J., and Dunn, P.A., 1993, The origin of high-frequency platform carbonate cycles and third-order sequences (Lower Ordovician El Paso Gp., west Texas); constraints from outcrop data and stratigraphic modeling. *Jour. Sed. Petrol.*, v. 63, no. 3, p. 318-359.
- Hall, J., 1851, Lower Silurian System; Upper Silurian and Devonian Series, *in* Foster, J.W. and Whitney, J.D., eds., Report on the geology of the Lake Superior land district, pt. 2: U.S. 32nd Congress Special Session, Senate Executive Document 4, p. 140-166; *Amer. Jour. Sci.*, 2nd series, v. 17, p. 181-194.
- Hambrey, M.J., 1985, The Late Ordovician-Early Silurian glacial period. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, v. 51, p. 273-289.
- Ingell, E.D., Bustin, R.M., and Van Cappellen, P., 1993, Influence of water column anoxia on the burial and preservation of carbon and phosphorus in marine shales. *Geochimica Acta*, v. 57, p. 303-

316.

- James, N.P., 1990, Cool water carbonate sediments: Viable analogues for Paleozoic limestones? 13th Int. Sedimentol. Cong. Nottingham, p. 275.
- James, N.P. and Bourque, P.A., 1992, Reefs and mounds, *in* Facies models-response to sea level change, Walker, R.G. and James, N.P., eds., Geological Society of Canada, p. 323-347.
- James, N.P. and Bone Y., 1994, paleoecology of cool-water, subtidal cycles in Mid-Cenozoic limestones, Eucla platform, southern Australia. *Palaios*, v. 9, p. 457-476.
- Jenkins, H.C., 1974, Origin of red nodular limestones (Ammonitico rosso, Knollenkalke) in the Mediterranean Jurassic: a diagenetic model. *Spec. Publs. Int. Assoc. Sediment.*, v. 1, p. 249-271.
- Jervey, M.T., 1988, Quantitative geological modeling of siliciclastic rock sequences and their seismic expression, *in* Wilgus, C.K., et al., eds., Sea level changes-An integrated approach: SEPM Special Publication 42, P. 47-69.
- Jones, B. and Dixon, O.A., 1976, Storm deposits in the Read Bay Formation (Upper Silurian), Somerset Island, Arctic Canada (an application of Markov Chain Analysis). *Jour. Sed. Petrol.*, v. 46, p. 393-401.
- Kay, G.M., 1935, Ordovician System in the Upper Mississippi Valley, *in* Kansas Geological Society 9th Annual Field Conference Guidebook, p. 281-295.
- Kennedy, W.J. and Garrison, R.E., 1975, Morphology and genesis of nodular chalks and hardgrounds in the Upper Cretaceous of Southern England. *Sedimentology*, v. 22, p. 311-386.
- Kinsman, D.J.J. and Holland, H.D., 1969, The co-precipitation of cations with CaCO₃ IV. The co-precipitation of Sr²⁺ with aragonite between 16° and 96°C. *Geochem. Cosmochem. Acta* v. 33, p. 1-17.

- Kolata, D.R., Frost, J.K., and Huff, W.D., 1986, K-bentonites of the Ordovician Decorah Subgroup, Upper Mississippi Valley: Correlation by chemical fingerprinting. Illinois State Geological Survey, Circular 537, 30p.
- Kreisa, R.D., 1981, Storm-generated sedimentary structures in subtidal marine facies with examples from the Middle and Upper Ordovician of southwestern Virginia. *Jour. Sed. Petrol.*, v. 51, no. 3, p. 823-848.
- Kreisa, R.D. and Bambach, R.K., 1982, The role of storm processes in generating shell beds in Paleozoic shelf environments, *in* Einsele, G. and Seilacher, A. eds., *Cyclic and event stratification*, p. 200-207.
- Laporte, L.F., 1969, Recognition of a transgressive carbonate sequence with an epeiric sea: Helderberg Group (Lower Devonian) of New York State, *in* Friedman, G.M. ed., *Depositional Environments in Carbonate Rocks*, SEPM, Spec. Pub. 14, p. 98-119.
- Laporte, L.F. and Imbrie, J., 1964. Phases and facies in the interpretation of cyclic deposits. *Kansas Geological Survey Bull.* 169, v. 1, P. 249-263.
- Lavoie, D., 1995, A Late Ordovician high-energy temperate-water carbonate ramp, southern Quebec, Canada: implications for Late Ordovician oceanography. *Sedimentology*, v. 42, p. 95-116.
- Lees, A. and Buller, A.T., 1972, Modern temperate-water and warm water shelf carbonate sediments contrasted. *Mar. Geol.*, v. 13, p. M67-M73.
- Leggett, J.K., McKerrow, W.S., Cocks, L.R.M., and Rickards, R.B., 1981, Periodicity in the early Palaeozoic marine realm. *Jour. geol. Soc. London*, v. 138, p.167-176.
- LoDuca, S.T., 1986, Stratigraphy of the Middle Ordovician Sinnipee Group in northeastern Wisconsin: [M.S. thesis]; University of Wisconsin-Milwaukee, 52 p.

- Long, J.D., 1988, Sedimentology of the Glenwood Member of the Middle Ordovician St. Peter Sandstone of southern Wisconsin: [M.S. thesis]; University of Wisconsin-Madison, 133 p.
- Matthews, R.K., 1966, Genesis of Recent lime mud in southern British Honduras. *Jour. Sed. Petrol.*, v. 36, p. 428-454.
- McCrossan, R.G., 1958, Sedimentary 'boudinage' structures in the Upper Devonian Ireton Formation of Alberta. *Jour. Sed. Petrol.*, v. 28, p. 316-320.
- McKerrow, W.S., 1979, Ordovician and Silurian changes in sea level. *Jour. geol. Soc. Lond.*, v. 136, p. 137-145.
- Miller, K.B., Brett, C.E., and Parsons, K.M., 1988, The palaeoecologic significance of storm-generated disturbance within a Middle Devonian muddy epeiric sea. *Palaios*, 1988, v. 3, p. 35-52.
- Moretti, G., 1971, Reference section for Paleozoic rocks in eastern Wisconsin: Van Driest no. 1, Sheboygan county: [M.S. Thesis]; University of Wisconsin-Milwaukee, 137 p.
- Mossler, J.H., 1985, Sedimentology of the Middle Ordovician Platteville Formation, southeastern Minnesota. Minnesota Geological Survey, Reports of Investigations 33, 27p.
- Mullins, H.J., Neumann, A.C., Wilber, R.J., and Boardman, M.R., 1980, Nodular carbonate sediments on Bahamian slopes: possible precursors to nodular limestones. *Jour. Sed. Petrol.*, v. 50, p. 117-131.
- Nelson, C.S., Hancock, G.E., and Kamp, P.J.J., 1982, Shelf to basin, temperate skeletal carbonate sediments, Three Kings Plateau, New Zealand. *Journal of Sedimentary petrology*, v. 52, no. 3, p. 717-732.
- Neumann, A.C. and Land, L.S., 1975, Lime mud deposition and calcareous algae in the Bight of Abaco, Bahamas: a budget. *Jour. Sed. Petrol.*, v. 45, p. 763-786.
- Neumann, A.C., Kofoed, J.W., and Keller, G.H., 1977, Lithoherms on the

Straits of Florida. *Geology*, v. 5, p. 4-10.

- Nitecki, M.H., 1972, The paleogeographic significance of receptaculitids. *Internat. Geol. Cong., 24th, Montreal, Proc. 7.* p. 303-309.
- Ostrom, M.E., 1969, Champlainian Series (Middle Ordovician) in Wisconsin. *Amer. Assoc. Petrol. Geol. Bull.*, v. 53, p. 671-678.
- Ostrom, M.E., 1967a, Paleozoic stratigraphic nomenclature for Wisconsin: *Wis. Geol. and Natural History Survey, Information Circular 8.*
- Ostrom, M.E., 1967b, Geologic cross section, Alger county, Michigan-Walworth county, Wisconsin: *Michigan Basin Geological Society Annual Field Excursion*, p. 36-41.
- Ostrom, M.E., 1987a, Middle Ordovician rocks at Potosi Hill, Wisconsin. *Geol. Soc. Amer. Centennial Field Guide-North-Central Section*, p. 201-204.
- Ostrom, M.E., 1987b, Middle Ordovician Platteville Formation, Hoadley Hill, Wisconsin. *Geol. Soc. Amer. Centennial Field Guide-North-Central Section*, p. 205-208.
- Palmer, T.J., 1982, Cambrian to Cretaceous changes in hardground communities. *Lethaia*, v. 15, p. 309-323.
- Plint, A.G., 1988, Sharp-based shoreface sequences and "offshore bars" in the Cardium Formation of Alberta: their relationship to relative changes in sea level, *in* Wilgus, C.K., et al., eds., *Sea level changes-An integrated approach: SEPM Special Publication 42*, P. 357-370.
- Posamentier, H.W., Jervey, M.T., and Vail, P.R., 1988, Eustatic controls on clastic deposition I - Conceptual framework, *in* Wilgus, C.K., et al., eds., *Sea level changes-An integrated approach: SEPM Special Publication 42*, P. 109-124.
- Prokopovich, M., 1955, The nature of corrosion zones in the Middle Ordovician of Minnesota. *Jour. Sed. Petrol.*, v. 25, no. 3, p.

207-215.

- Purser, B.H., 1969, Syn-sedimentary marine lithification of Middle Jurassic limestones in the Paris basin. *Sedimentology*, v. 12, p. 205-230.
- Railsback, L.B., Ackerly, S.C., Anderson, T.F., and Cisne, J.L., 1990, Paleontological and isotope evidence for warm saline deep waters in Ordovician oceans. *Nature*, v. 343, p.156-159.
- Read, J.F., 1985, Carbonate platform facies models. *Bull. Amer. Assoc. Petrol. Geol.*, v. 69, 1-21.
- Robbins, L.L. and Blackwelder, P.L., 1992, Biochemical and ultrastructural evidence for the origin of whittings: A biologically induced calcium carbonate precipitation mechanism. *Geology*, v. 20, p. 464-468.
- Roehl, P.W., 1967, Stony Mountains (Ordovician) and Interlake (Silurian) facies analogs of Recent low-energy marine and subaerial carbonates, Bahamas. *Bull. Amer. Assoc. Petrol. Geol.*, v. 51, p. 1979-2032.
- Ross, R.J., Jr., 1976, Ordovician Sedimentation in the western United States, *in* Bassett, M.G., ed., *The Ordovician System: proceedings of a Palaeontological Association symposium*, Birmingham, p. 73-105.
- Ross, C.A. and Ross J.R.P., 1995, North American Ordovician depositional sequences and correlations, *in* Cooper, J.D., Droser, M.L., and Finney, S.C., eds., *Ordovician Odyssey, short papers for the seventh international symposium on the Ordovician System*, Las Vegas, p. 309-313.
- Scotese, C.R., Bambach, R.K., Barton, C., Van der Voo, R. and Ziegler, A.M., 1979, Paleozoic base maps. *Journal of Geology*, 87, p. 217-277.
- Sepkoski, J.J. Jr., 1982, Flat pebble conglomerates, storm deposits, and the Cambrian bottom fauna, *in* Einsele, G. and Seilacher, A., eds., *Cyclic and Event Stratification*, Berlin, Springer-Verlag, p. 371-385.

- Sheehan, P.M. and Schiefelbein, D.R.J., 1984, The trace fossil *Thalassinoides* from the Upper Ordovician of the eastern Great Basin: deep burrowing in the early Paleozoic. *Jour. Paleontology*, v. 58, p. 440-447.
- Shinn, E.A., 1968, Practical significance of bird's eye structures in carbonate rocks. *Jour. Sed. Petrol.*, v. 38, p. 215-223.
- Shinn, E.A., 1969, Submarine lithification of Holocene carbonate sediments in the Persian Gulf. *Sedimentology*, v.12, p. 109-144.
- Sloss, L.L., 1963, Sequences in the cratonic interior of North America. *Geol. Soc. Amer. Bull.*, v. 74, p. 93-114.
- Smith, G.L., 1991, Sequence stratigraphy and diagenesis of the Lower Ordovician Prairie Du Chien Group in the Wisconsin Arch and in the Michigan Basin: [M.S. thesis]; University of Wisconsin-Madison, 265 p.
- Specht, R.W. and Brenner, R., 1979, Storm-wave genesis of bioclastic carbonates in Upper Jurassic epicontinental mudstones, east-central Wyoming. *Jour. Sed. Petrol.*, v. 49, p. 1307-1322.
- Spjeldnaes, M., 1981, Lower Palaeozoic climatology, *in* Holland, C.H., ed., *Lower Palaeozoic of the Middle East, eastern and southern Africa, and Antarctica*: Chichester, United Kingdom, Wiley, p. 199-256.
- Stauffer, C.R., 1925, Mineralization of the Platteville-Decorah contact zone in the Twin City Region. *Geol. Soc. Amer. Bull.*, v. 36, p. 615-622.
- Steinen, R.P., Swart, P.K., Shinn, E.A., and Lidz, B.H., 1988, Bahamian lime mud: The algae didn't do it. *Geol. Soc. Amer. Abstracts-with-Programs*, v. 20, no. 7, p. 209.
- Stith, D.A., 1979, Chemical composition, stratigraphy, and depositional environments of the Black River Group (Middle Ordovician), southwestern Ohio. Ohio Geological Survey, Reports of

Investigations 113, 36p.

- Templeton, J.S. and Willman, H.B., 1963, Champlainian Series (Middle Ordovician) in Illinois: Illinois State Geological Survey Bulletin 89, 260 p.
- Thickpenny, A. and Leggett, J.K., 1987, stratigraphic distribution and palaeo-oceanographic significance of European early Palaeozoic organic-rich sediments, *in* Marine Petroleum Source Rocks, Geol. Soc. Spec. Publs, no. 26, p. 231-247
- Vail, P.R., Mitchum, R.M., and Thompson, S., III, 1977, Seismic stratigraphy and global changes of sea level, Part 3: relative changes of sea level from coastal onlap, *in* Payton, C.E. (ed.), Seismic Stratigraphy - Application to Hydrocarbon Exploration: American Association of Petroleum Geologists, Memoir 26, p. 63-97.
- Van der Voo, R., 1988, Paleozoic paleogeography of North America, Gondwana, and intervening displaced terranes: Comparisons of paleomagnetism with paleoclimatology and biogeographical patterns. Geol. Soc. Amer. Bull. v. 100, p. 311-324.
- Van Wagoner, J.C., Michum, R.M., Jr., Campion, K.M. and Rahmanian, V.D., 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops. Amer. Assoc. Petrol. Geol., Methods in Exploration Series, no. 7, 55p.
- Walker, K.R., 1973, Stratigraphy and environmental sedimentology of Middle Ordovician Black River Group in the Type Area-New York State. New York State and Science Service Bulletin 419, 43p.
- Walker, R.G. and James, 1992, Facies Models-Response to Sea Level Change. Geological Assoc. Canada, 409p.
- Walker, R.G. and Plint, A.G., 1992, Wave- and storm-dominated shallow marine systems, *in* Walker, R.G. and James, N.P. eds., Facies Models-Response to Sea Level Change. Geol. Assoc. Canada, p. 219-238.

- Wanless, H.R., 1979, Limestone response to stress: pressure solution and dolomitization. *Jour. Sed. Petrol.*, v. 49, p. 439-462.
- Webers, G.F., 1966, The Middle and Upper Ordovician faunas of Minnesota. Minnesota Geological Survey, Spec. Publs. SP-4, 123p.
- Wilcer, B.L., 1989, Diagenetic and depositional history and facies relationships of shallow, subtidal deposits of the Ordovician Platteville and Galena Groups at Kentland, Indiana: [M.S. thesis]; Indiana University, 106p.
- Wilkinson, B.H., Janecke S. U., and Brett C. E., 1982, Low-magnesian calcite cement in Middle Ordovician hardgrounds from Kirkfield, Ontario. *Jour. Sed. Petrol.*, V. 52, No. 1, p. 47-57.
- Willman, H.B. and Kolata, D.R., 1978, The Platteville and Galena Groups in northern Illinois: Illinois State Geological Survey Circular 502, 75 p.
- Wilson, J.L., 1975, Carbonate Facies in Geologic History. New York, Springer-Verlag, 471p.
- Winfrey, K.W., 1983, Depositional environments of the St. Peter Sandstone of the upper Midwest: [M.S. thesis]; University of Wisconsin-Madison, 114p.
- Witzke, B.J., 1980, Middle and Upper Ordovician paleogeography of the region bordering the Transcontinental Arch, *in* Paleozoic paleogeography of the West-central United States, Fouch, T.D. and Magathan, E.R., eds., SEPM Rocky Mountain Section, Denver, Colo., p. 1-18.
- Witzke, B.J., 1987, Models for circulation patterns in epicontinental seas applied to Paleozoic facies of North America Craton. *Paleoceanography*, v. 2, p. 229-248.
- Witzke, B.J., 1990, Paleoclimate constraints for Paleozoic paleolatitudes of Laurentia and Euramerica, *in* McKerrow, W., S., and Scotese, C. R., eds. Paleozoic Paleogeography and Biogeography: Geological Society Memoir No. 12, p. 57-73.

- Witzke, B.J., 1993, Shallowing-upward cyclic patterns within larger-scale transgressive-regressive (T-R) sedimentary sequences, St. Peter through Decorah Formation, Ordovician, Iowa area. Geological Society of America Abstracts with Programs, v. 25, no. 3, p. 90.
- Witzke, B.J. and Kolata, D. R., 1989, Changing structural and depositional patterns, Ordovician Champlainian and Cincinnati Series of Iowa-Illinois, *in* Ludvigson G. A., and Bunker, B. J., eds., New Perspectives on the Paleozoic History of the Upper Mississippi Valley-An examination of the Plum River Fault Zone: Guidebook for the 18th annual field conference of the Great Lakes Section, Society of Economic Paleontologists and Mineralogists, p. 55-77.

Appendix A. MEASURED LOCALITIES OF THE SINNIPEE GROUP.

I. OUTCROP LOCALITIES

A. Jefferson County

1. Active quarry on north side of county Highway M, 1/2 mile east of US Highway 12, 1 mile southeast of Fort Atkinson, Jefferson Co. (Abbreviation: FT, Total Thickness: 23m).

B. Dodge County

2. Active quarry on east side of US Highway 16, 2.5 mile north of Watertown, Dodge Co. (WT, 19m).
3. Abandoned quarry on west side of county Highway K, 3 mile northwest of Watertown, Dodge Co. (RW, 4m)
4. Abandoned quarry on west side of Fairwood Road, 1 mile north of state Highway 16, 60, 2 mile west of Lowell, Dodge Co. (LW, 8m)
5. Active quarry on north side of county Highway W, 1 1/2 mile southeast of Beaver Dam, Dodge Co. (BD, 13m)
6. Abandoned quarry on west side of county Highway CP, 1 1/2 mile west of Stony Quarry point, Dodge Co. (LL, 5m)
7. Active quarry on north side of Spruce Road between state Highway 33 and county Highway W, 2 1/2 mile north of Beaver Dam, Dodge Co. (SP, 12m)
8. Active quarry on south side of Breeze Point Road, just near the intersection with county Highway A, 3 1/2 mile north of Beaver Dam, Dodge Co. (BC, 6m)

C. Fond du Lac, Green Lake Counties

9. Active quarry on east side of U.S. Highway 26 (Business 151),

northeast corner of Waupun, Fond du Lac Co., WI. (WP, 11m)

10. Active quarry on east side of state Highway 49, 1/2 mile northwest of Waupun, Fond du Lac Co. (WN, 9m)
11. Active quarry on west side of state Highway 49, 1 mile northwest of Waupun, Fond du Lac Co. (BR, 14m)
12. Active quarry on north side of county Highway I, 1 mile southeast of Markesan, Green Lake Co. (MK, 10m)
13. Abandoned quarry on north side of county Highway I (Mackford Hill Road), 2 1/2 mile east of Markesan, Green Lake Co. (MH, 6m)
14. Active quarry on north side of Dartford Road, just east of St Patrick Cemetery, Ripon, Fond du Lac Co. (RP, 14m)
15. Roadcut on east side of Arcade Glen Road, just west of Ripon, Fond du Lac Co. (AG, 8m)

D. Winnebago County

16. Active quarry on west side of Highway. 26, just on the border to Fond du Lac Co, 6 mile north of Rosandale, Fond du Lac Co. (RD, 9m).

E. Dane County

17. Active quarry on south side of Highway 151, Stone Quarry Road, 2 mile northeast of Sun Prairie, Dane Co. (SN, 15m).

II. CORE LOCALITIES

A. Jefferson County

JE: NE1/4 of the SE1/4, Section 21, Township 8N, Range 16E.

B. Waukesha County

WK-1: NE1/4 of the SW1/4, Section 18, Township 8N, Range 17E.

WK-2: SW1/4 of the NE1/4, Section 21, Township 6N, Range 17E.

WK-3: SE1/4 of the NW1/4, Section 33, Township 5N, Range 17E.

C. Racine County

RA: NW1/4 of the SE1/4, Section 35, Township 3N, Range 20E.

D. Kenosha County

KE: SW1/4 of the SW1/4, Section 2, Township 1N, Range 21E.

APPENDIX B. MEASURED SECTIONS OF SINNIPEE GROUP, E. WI.

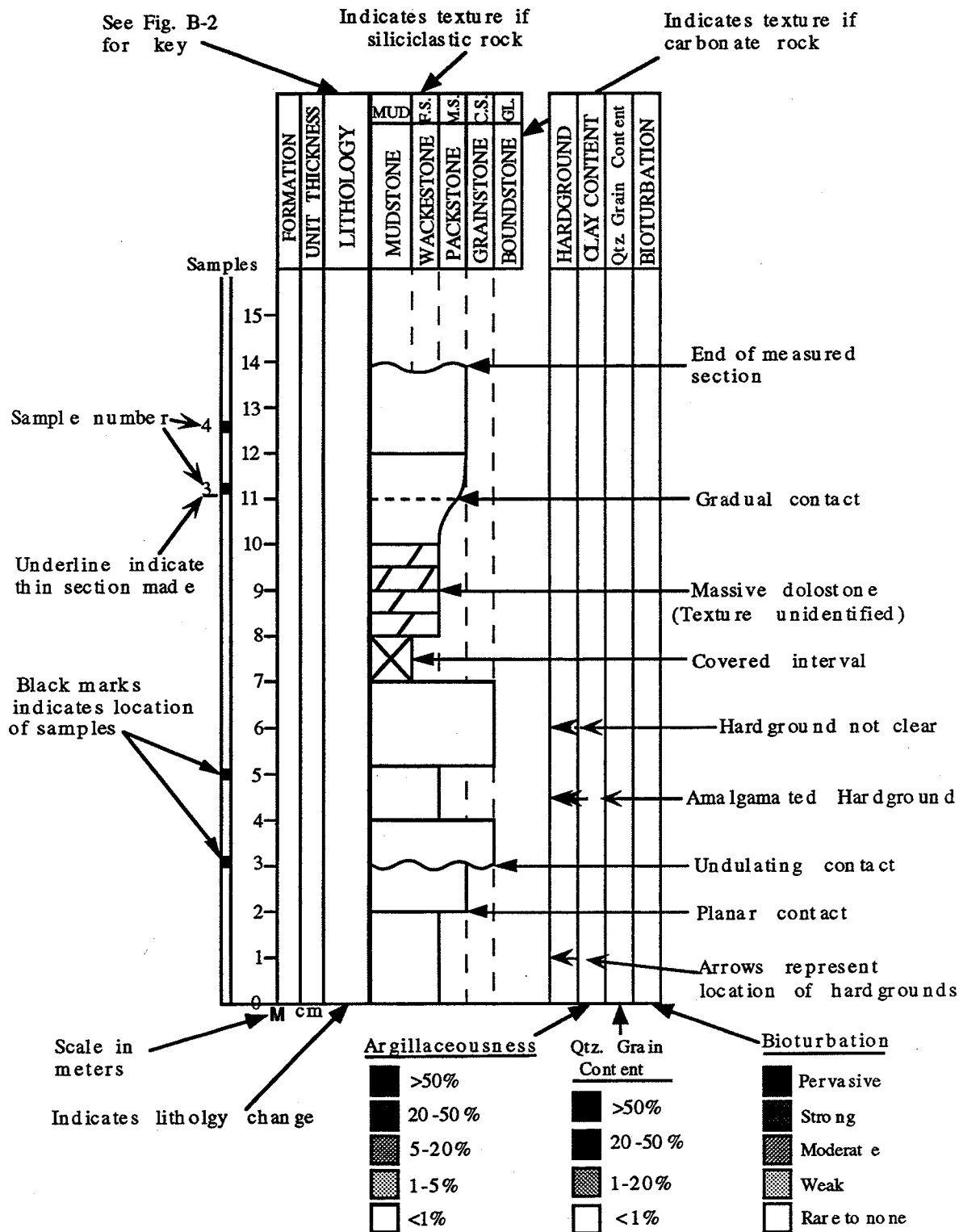





























Fig. B-1. Key to reading columnar sections.










LITHOLOGY

 Sand/ Sandstone	 Limestone (Lm.)	 Shale	 Cherty Dolostone
 Sandy Shale	 Dolostone (Dm.)	 Calcareous shale	 Sandy Limestone
 Poorly sorted Ss.	 Argillaceous Lm.	 Dolomitic shale	 Sandy Dolostone
 Conglomerate	 Argillaceous Dm.	 Cherty Lst	 Dolomitic Ss.

PHYSICAL STRUCTURES

 Current Ripple	 Trough Cross-strat.	 Large-scale Cross Bedding
 Climbing Ripples	 Parallel Lamination	 Hummocky Cross-strat.
 Oscillatory Ripples	 High Angle Tabular Bedding	 Mud Cracks
	 Low Angle Tabular Bedding	 Nodular Bedding

LITHOLOGIC ACCESSORIES

 Peloids	 Intraclasts	 Shale Lamina
 Quartz silts	 Intraclasts (black)	 Chert (white)
 Calcite patch	 Phosphate Grains	 Chert (colored)

FOSSILS/ Bioclasts(molds)


















 Algae, (undifferentiated)	 Bryozoa (tube-like)	 Brachiopods
 Bryozoa (fenestellid)	 Indicate bioclasts / molds	 Trilobites
 Corals (solitary)	 Crinoids	 Corals (colonial)
 Echinoderms	 Cephalopods	 Gastropods
 receptaculites	 Pelecypods	 Bioclasts (undifferentiated)
 Graptolites	 Ostracods	

Fig. B-2. Reading Key for sedimentary structures, lithology, and grain types.

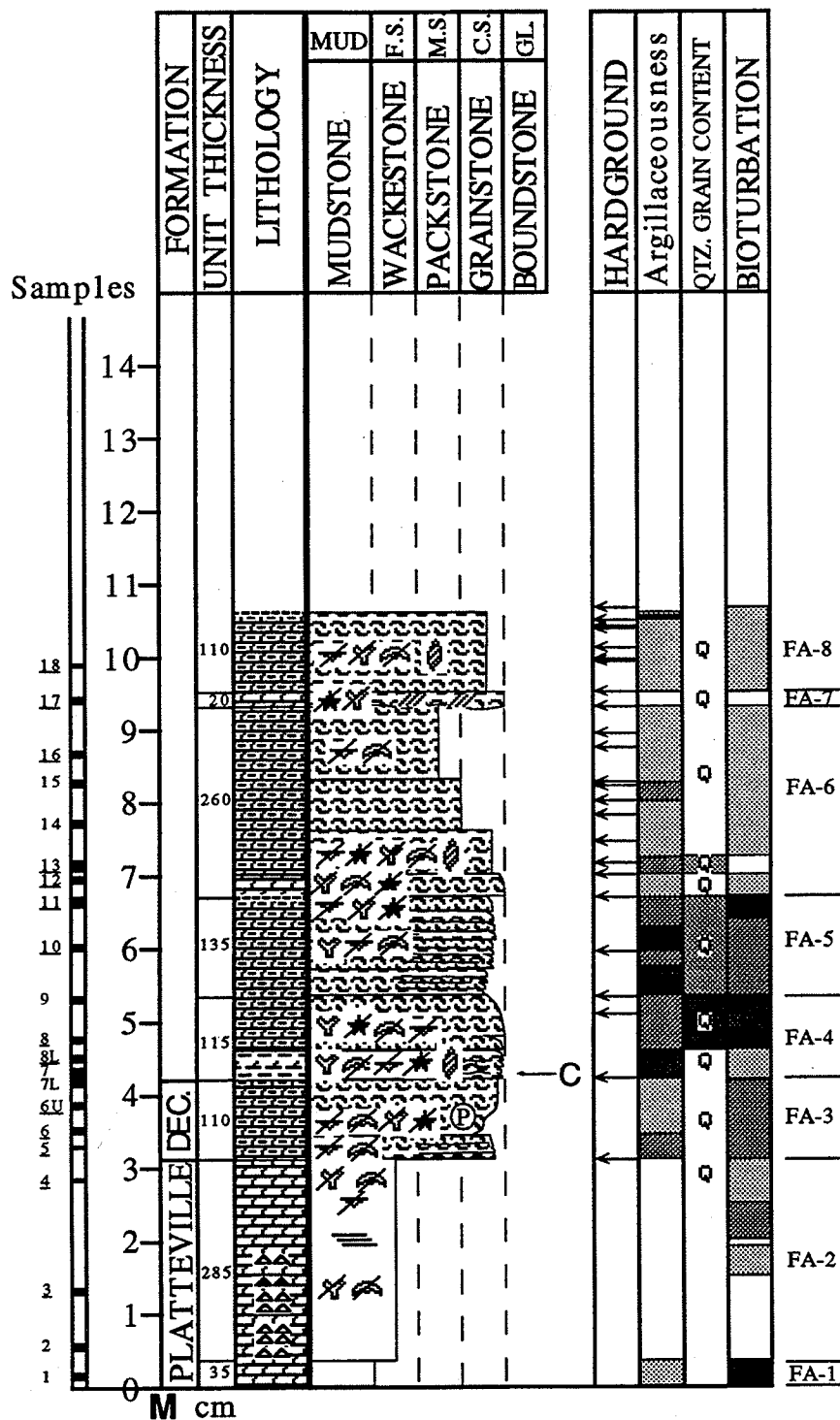


Fig. B-3. Columnar section measured from the Fort Atkinson Qr., Locality 1. C (arrow) represents the horizon from which the conodont sample was taken. Descriptions of units followed next.

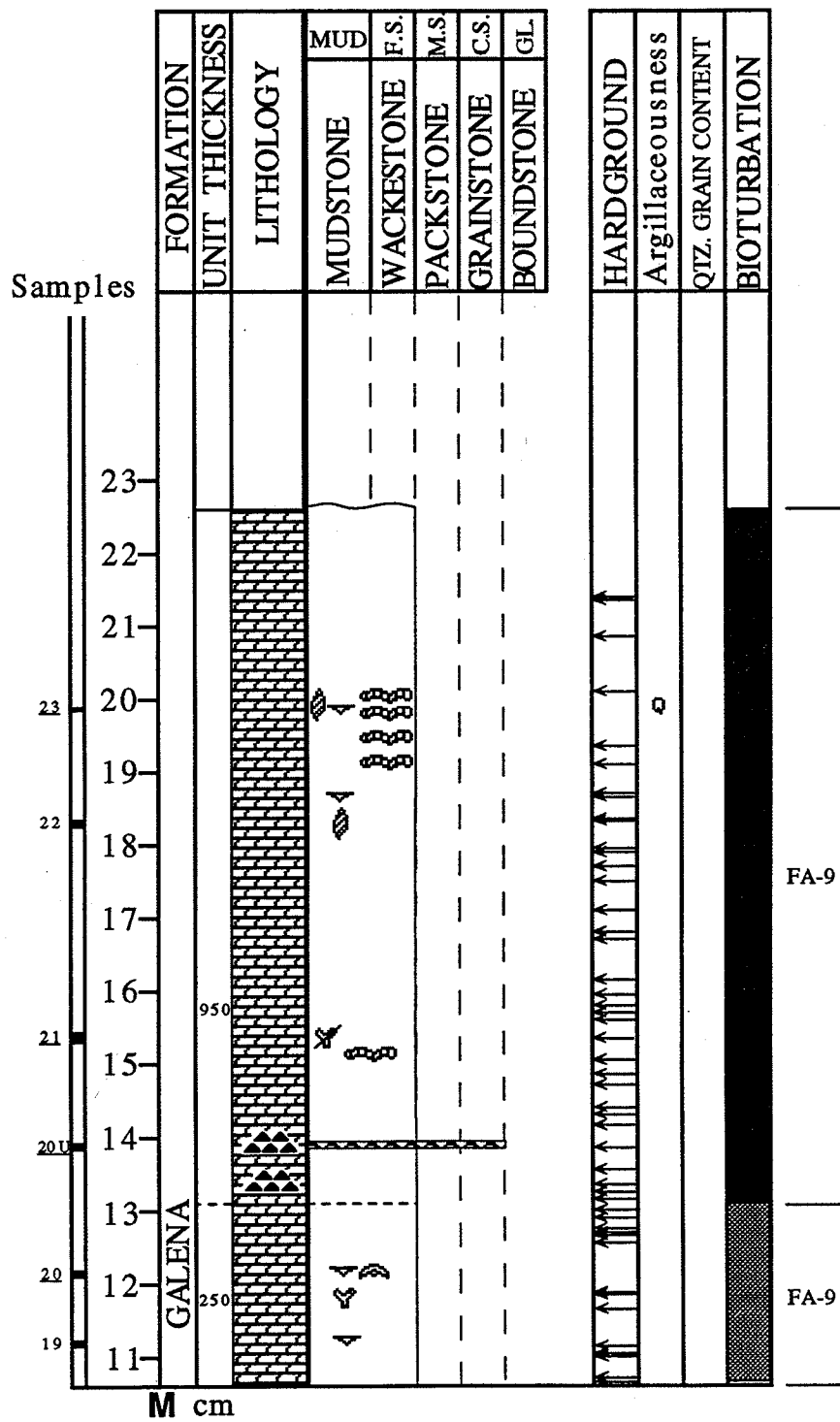


Fig. B-3. Continued.

Description

Rock Unit No.
Top of section

FA-10

Dolostone, medium- to coarse-crystalline, carbonate; gradually more porous upward; locally dark purplish brown chert nodules present; medium- to thick-bedded; buff yellow; wackestone to packstone(?), but the texture is very difficult to define; moderate to strongly bioturbated with large burrows 1-2 cm in diameter filled with coarser crystalline dolomite, minor 1-3 mm lined burrows; very porous with irregularly distributed vesicular porosity throughout with minor moldic to vuggy porosity; brachiopods and bryozoans abundant, gastropod molds common, receptaculites common particularly in the upper part; contains abundant hardgrounds.
(FA23,22,21,20U)

FA-9

Dolostone, fine- to medium-crystalline, argillaceous-free except base; medium- to thick-bedded; buff yellow; gradually less argillaceous, thicker bedded, and more porous upward; fossiliferous mudstone to wackestone; moderately bioturbated with 0.3-1.0 cm-sized burrows, minor 1-3 mm lined burrows; vesicular porosities are common within burrows and molds partly or completely filled with coarse dolomite crystals; orthid brachiopods (*Platystrophia?*) and bryozoan molds common with occasional trilobite molds; contains abundant hardgrounds in 5-20 cm interval.
(FA20,19)

FA-8

Dolostone, medium- to coarse-crystalline, argillaceous; thin- to medium-bedded with thin green shale partings; yellowish gray; bioclastic packstone to grainstone; weakly bioturbated with 1-4 mm thick burrows filled with shaly material; slightly vuggy and vesicular porosity outside of large burrows; gastropods common; contains abundant hardgrounds; bounded above by a prominent shale parting.
(FA18)

FA-7

Dolostone, medium- to coarse-crystalline, carbonate; comprises two amalgamated bioclastic grainstone beds with a shaly parting between them; cross-bedded with 20 degree plunge; vesicular moldic porosities abundant by leaching of bioclasts.
(FA17)

FA-6

Dolostone, fine- to medium-crystalline, contains numerous argillaceous seams; gradually less argillaceous and grainy upward; medium- to thick-bedded; medium gray on fresh beds, greenish buff yellow on weathered beds; bioclastic wackestone to grainstone; weakly to moderately bioturbated with 1-5 mm wide burrows filled with argillaceous material; contains brachiopods, trilobites, crinoids, and bryozoan fragments; gastropod molds present; contains numerous hardgrounds.
(FA16,15,14,13,12)

FA-5

Dolostone, fine- to medium-crystalline; greenish yellow to greenish gray; thin- to medium-bedded; shaly bioclastic packstone to grainstone containing brachiopod, bryozoa,

crinoid, and trilobite fragments; less shaly in upper part; moderate to strongly bioturbated with 1-5 mm burrows filled with green shale; contains quartz silts (2-3%); beds just below hardgrounds are less shaly.

(FA11,10)

FA-4

Dolostone, fine- to medium-crystalline; gray on fresh surfaces and greenish yellow on weathered surfaces; thin- to medium-bedded; bioclastic packstone to grainstone interbedded with bioclast rich shale; moderate to strongly bioturbated with 2-6 mm burrows filled with shaly material; gradually thicker bedded, less argillaceous, and more bioturbated upward; grainstone beds contain fragments of trilobite, brachiopod, bryozoans, and crinoids with some phosphate grains of 0.2 mm size; trepostome bryozoans are concentrated in grainstone beds; graded bedding; upper beds are slightly vuggy with moldic porosity; contains terrigenous silts with up to 20%.

(FA9,8,8L,7)

FA-3

Dolostone, fine- to medium-crystalline; brown to greenish gray; thin- to medium-bedded with thin phosphorous/argillaceous partings in 1-5 cm interval; bioclastic wackestone to packstone with intercalating grainstones; moderately bioturbated; contains fragments of brachiopods, trilobites, bryozoans, and crinoids; lower part is thin bedded with shaly partings and contains abundant brachiopods; thicker-bedded upward; bounded below by an unconformity and above by a prominent hardground.

(FA7L,6U,6,5)

FA-2

Dolostone, fine-crystalline, ; locally white to dark purplish brown chert nodules present; yellowish buff; massive; fossiliferous mudstone with occasional thin laminations; contains brachiopod and bryozoan molds which sometimes show vesicular porosity when pore-filling dolomite crystals are partly or completely weathered out; inarticulate brachiopod (phosphate), bryozoans, trilobite fragments common; weakly bioturbated with 3-4 mm size burrows; contains quartz silts; capped by a prominent hardground on top.

(FA4,3,2)

FA-1

Dolostone, very fine-crystalline, slightly argillaceous; light gray with dark gray mottled burrows on fresh surfaces; strongly to pervasively bioturbated mudstone.

(FA1)

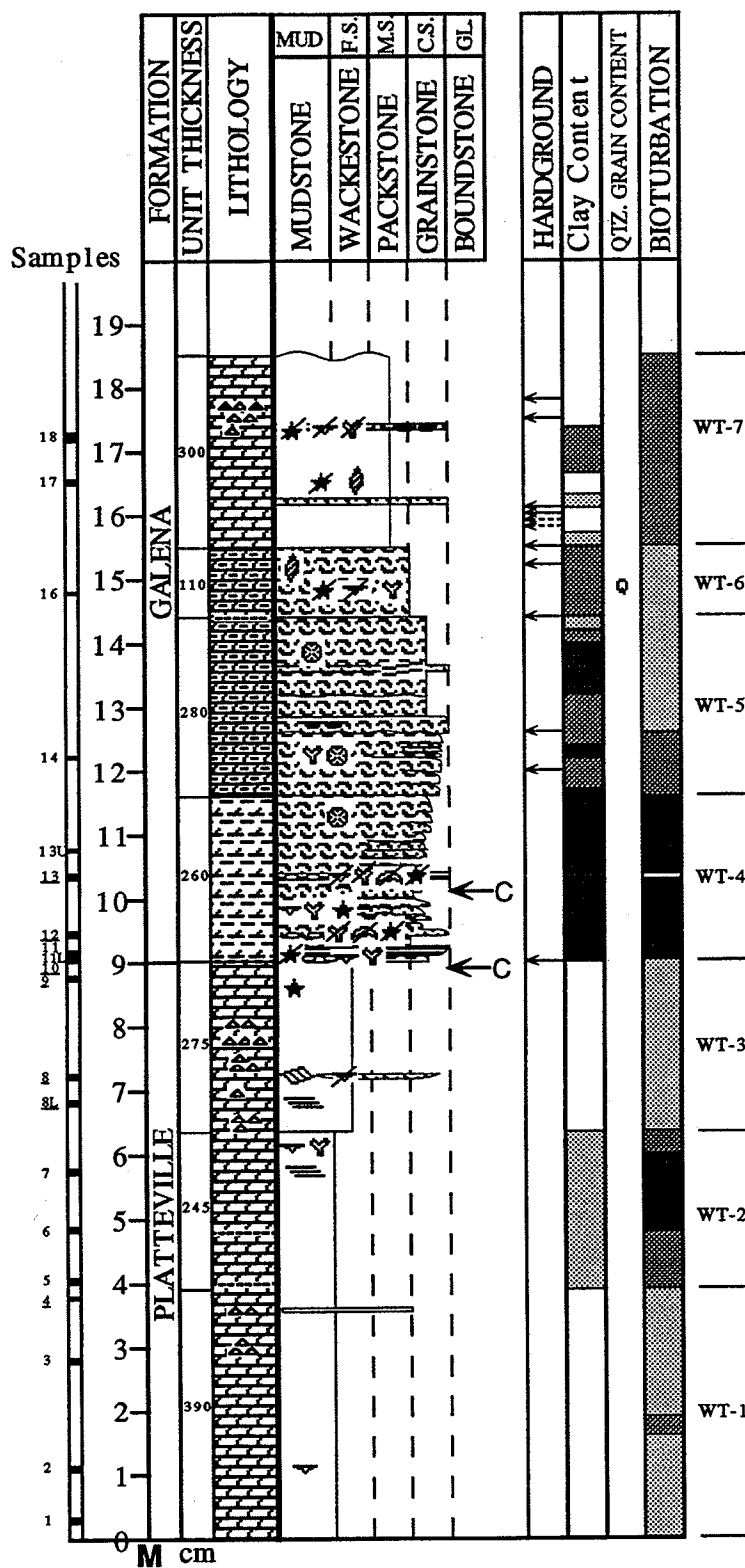


Fig. B-4. Columnar section measured from Watertown Qr., Locality 2. C (arrow) represents the horizon from which the conodont samples were taken. Descriptions of units followed next.

Description

Rock Unit No.
Top of section

WT-7

Dolostone, fine- to medium-crystalline, slightly argillaceous to argillaceous; gradually less argillaceous upward; buff yellow to greenish gray depending on weathering; bioclastic wackestone interbedded with argillaceous, bioclastic packstone with occasionally intercalating grainstone beds; medium-bedded; argillaceous-free beds show irregularly distributed vesicular porosities; brachiopods, crinoids, and large bryozoan fragments common; some grainstone beds contain cm-sized intraclasts in calcarenite matrix; moderately bioturbated by burrows, 1-6 mm in diameter; gastropod molds present; contains abundant hardgrounds.

(WT18,17)

WT-6

Dolostone, fine- to medium-crystalline, less argillaceous than below; gradually less argillaceous upward; greenish gray; argillaceous bioclastic packstone; contains hardgrounds and moldic porosities; some beds contain abundant bryozoan fragments of gravel size; contains terrigenous silts in about 3 %.

(WT16)

WT-5

Dolostone, medium- to coarse-crystalline, argillaceous to shaly; gray; thin- to medium-bedded with thin shaly partings; bioclastic packstone to grainstone mixed with clay due to bioturbation; less argillaceous than the unit below; three upward less argillaceous trends identified; rich in trepostome bryozoans, coral present; some grainstone beds are low angle cross-laminated, weakly bioturbated; dark intraclastic pebbles present at some grainstone beds; terrigenous silts present; a very prominent shaly parting is present on top of the unit.

(WT14)

WT-4

Dolostone, medium-crystalline, shaly; greenish gray; thin-bedded; shaly bioclastic packstone with intercalating grainstone beds; shaly material occur as burrow fillings as well as mm-thick partings between beds; some grainstone beds are laminated; moderately to strongly bioturbated by 2-10 mm-wide burrows filled with shale; orthid brachiopods (*Dalmanella*) and trepostome bryozoans abundant in shale partings on bedding plains with fragments of crinoids and trilobites; terrigenous silts present; bounded below by unconformity.

(WT13U,13,12,11,11L)

WT-3

Dolostone, fine- to medium-crystalline; light purplish gray; white chert nodules abundant; irregularly distributed vesicular to vuggy pores; medium- to thick-bedded; fossiliferous mudstone to wackestone with occasionally intercalating thin bioclastic packstone to grainstone beds; contains brachiopod molds and crinoids; contains more bioclasts upward; weakly bioturbated; terrigenous silts present in less than 1 %; contains ripple lamination locally; a very prominent, bored hardground is present on top of the unit.

(WT10,9,8,8L)

WT-2

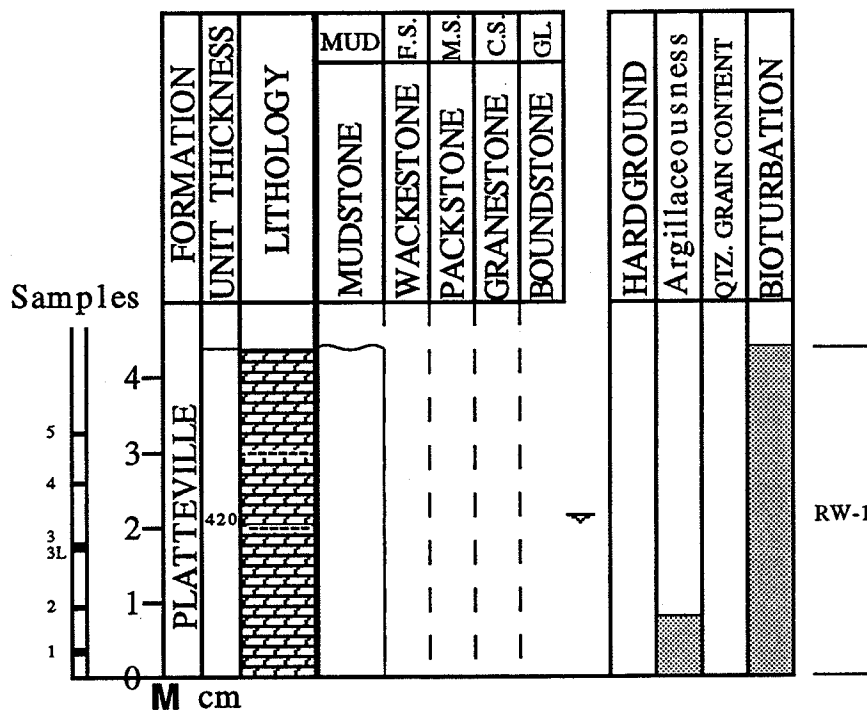
Dolostone, very fine-crystalline, argillaceous; light gray with dark gray mottlings; thin- to medium-bedded; moderately to strongly bioturbated mudstone.

(WT7,6,5)

WT-1

Dolostone, very fine-crystalline, slightly argillaceous; light purplish gray; medium-bedded; shows conchoidal fracture; white chert nodules present in the upper part; weakly bioturbated by horizontal burrows 2-4 mm in diameter, some are dark gray; contains inarticulate brachiopods (*Lingulella?*).

(WT4,3,2,1)



Description

Rock Unit No.
 Top of section

Rw - 1

Dolostone, very fine-crystalline; carbonate to slightly argillaceous, gradually less argillaceous upward; thin- to medium-bedded with wavy argillaceous partings; light purplish gray to buff yellow; weakly bioturbated with mostly horizontal burrows, 1-3 mm in diameter; mudstone with occasional thin bioclastic grainstone lense.
 (RW5,4,3,3L,2,1)

Fig. B-5. Columnar section measured from Richwood Qr., Locality 3.

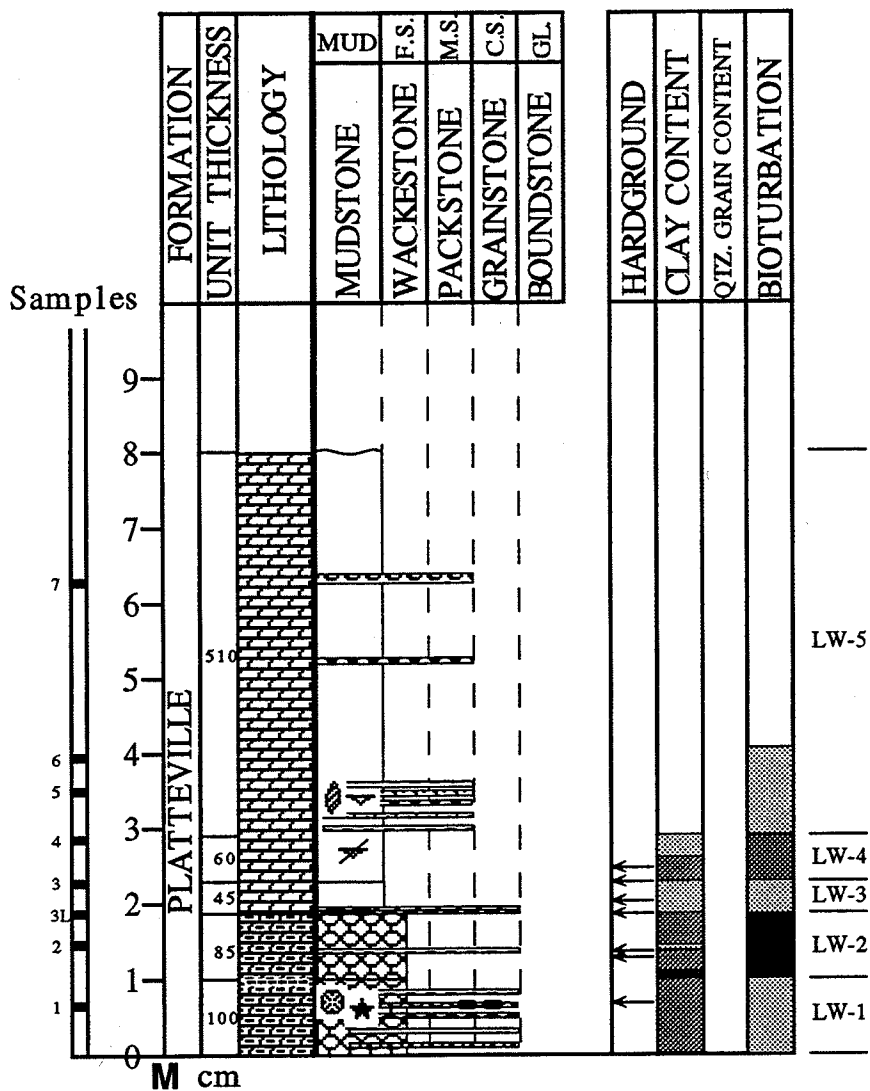


Fig. B-6. Columnar section measured from Lowell Qr., Locality 4. Descriptions of units followed next.

Description

Rock Unit No.
Top of section

LW-5

Dolostone, very fine-crystalline; relatively argillaceous-free; light purplish gray; thin- to medium-bedded; mudstone intercalated by occasional bioclastic packstone to grainstone beds; brachiopods (*Opikina*) common; mostly weakly bioturbated but dark gray-mottled in lower part.

(LW7,6,5)

LW-4

Dolostone, very fine-crystalline, argillaceous; greenish gray to light purplish gray; gradually purer upward with changing colors from green to purple; moderately bioturbated with 2-4 mm wide mottled burrows.

(LW4,3)

LW-3

Dolostone, fine-crystalline; medium-bedded; light purplish brown; mudstone with thin intra-bioclastic grainstones at base; weakly to moderately bioturbated; gradually purer upward.

(LW3)

LW-2

Dolostone, fine-crystalline, argillaceous to carbonate; medium-bedded; light purplish brown to greenish gray; fossiliferous mudstone with occasionally intercalating intra-bioclastic grainstone; moderately to strongly bioturbated; upward changes is gradational from the argillaceous, gray bed to the less argillaceous, brown beds whereas reverse is sharp; upper boundary is gradational.

(LW3L,2)

LW-1

Dolostone, fine- to medium-crystalline, argillaceous; gray to buff yellow; thin-bedded with dark gray shale partings; weakly to moderately bioturbated with horizontal burrows 2-5 mm in diameter; bioturbated mudstones interbedded with intra-bioclastic packstone to grainstone; some grainstone beds shows graded bedding; contains hardgrounds; bounded above by 1 cm thick green shale parting.

(LW1)

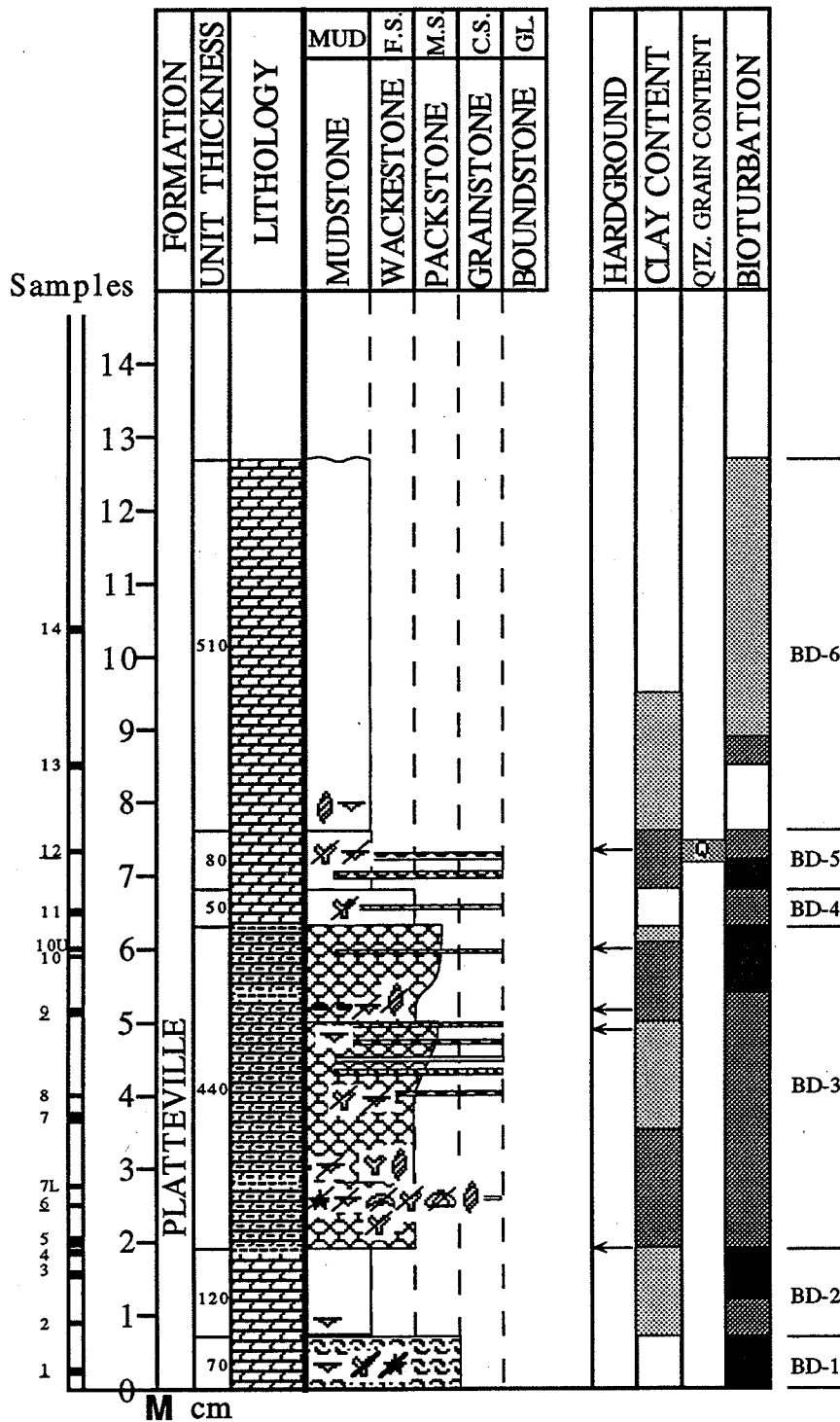


Fig. B-7. Columnar section measured from Beaver Dam Qr., Locality 5. Descriptions of units followed next.

Description

Rock Unit No.
Top of section

BD-6

Dolostone, very fine-crystalline; slightly argillaceous; thin-bedded mudstone; mostly weakly bioturbated; gradually less argillaceous upward; contains gastropods and brachiopods; locally patchy calcite present.

(BD14,13)

BD-5

Dolostone, very fine-crystalline, slightly argillaceous; thin-bedded mudstone with occasional intercalating grainstone; moderately to strongly bioturbated; gradually less bioturbated and less argillaceous upward; contains quartz silts with up to around 3%.

(BD12)

BD-4

Dolostone, fine- to medium-crystalline, relatively argillaceous-free; purplish brown to grayish buff; medium bedded; moderately bioturbated; fossiliferous mudstone to wackestone with 1-2 cm thick thin intercalating grainstones; calcite patches are concentrated locally.

(BD11)

BD-3

Dolostone, fine-crystalline; argillaceous, two gradually less argillaceous upward sequences; thin-bedded with nodular appearances; calcareous nodules are 0.5-1 cm in height and elongated laterally with more than 1 cm width; greenish gray to yellowish gray; moderately to strongly bioturbated with 2-3 cm horizontal burrows; bioclastic wackestone to packstone with intercalating thin intra-bioclastic grainstone beds; bryozoans, brachiopods, crinoids, trilobites common; gastropod (Maclurites) present; contains hardground and dark intraclasts.

(BD10U,10,9,8,7,7L,6,5)

BD-2

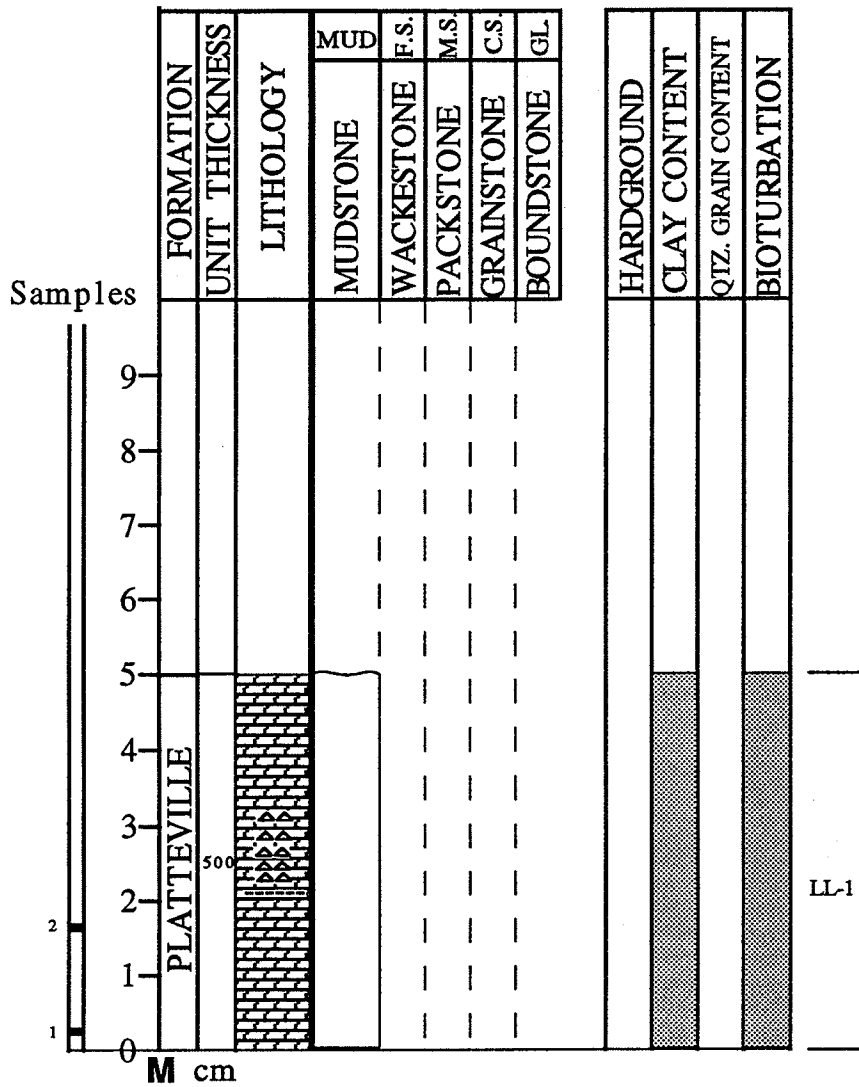
Dolostone, very fine-crystalline; argillaceous; medium-bedded; moderately to strongly bioturbated; gradually more bioturbated and less grainy upward; medium gray with dark gray mottled burrows 2-7 mm in diameter; mudstone to bioclastic wackestone; a sharp, prominent hardground on top.

(BD4,3,2)

BD-1

Dolostone, medium-crystalline; carbonate; medium to dark gray; medium-bedded; bioclastic packstone; strong to pervasively bioturbated with 1-6 mm wide burrows; orthid brachiopod (Campylorthis) molds present.

(BD1)



Description

Rock Unit No.
Top of section

LL-1

Dolostone, very fine-crystalline, slightly argillaceous; thin- to medium-bedded with wavy argillaceous partings; light purplish gray to buff yellow; weakly to moderately bioturbated with mostly horizontal burrows, 2-6 mm in diameter; mudstone; contains white chert nodules.

(LL2,1)

Fig. B-8. Columnar section measured from Lost Lake Qr., Locality 6.

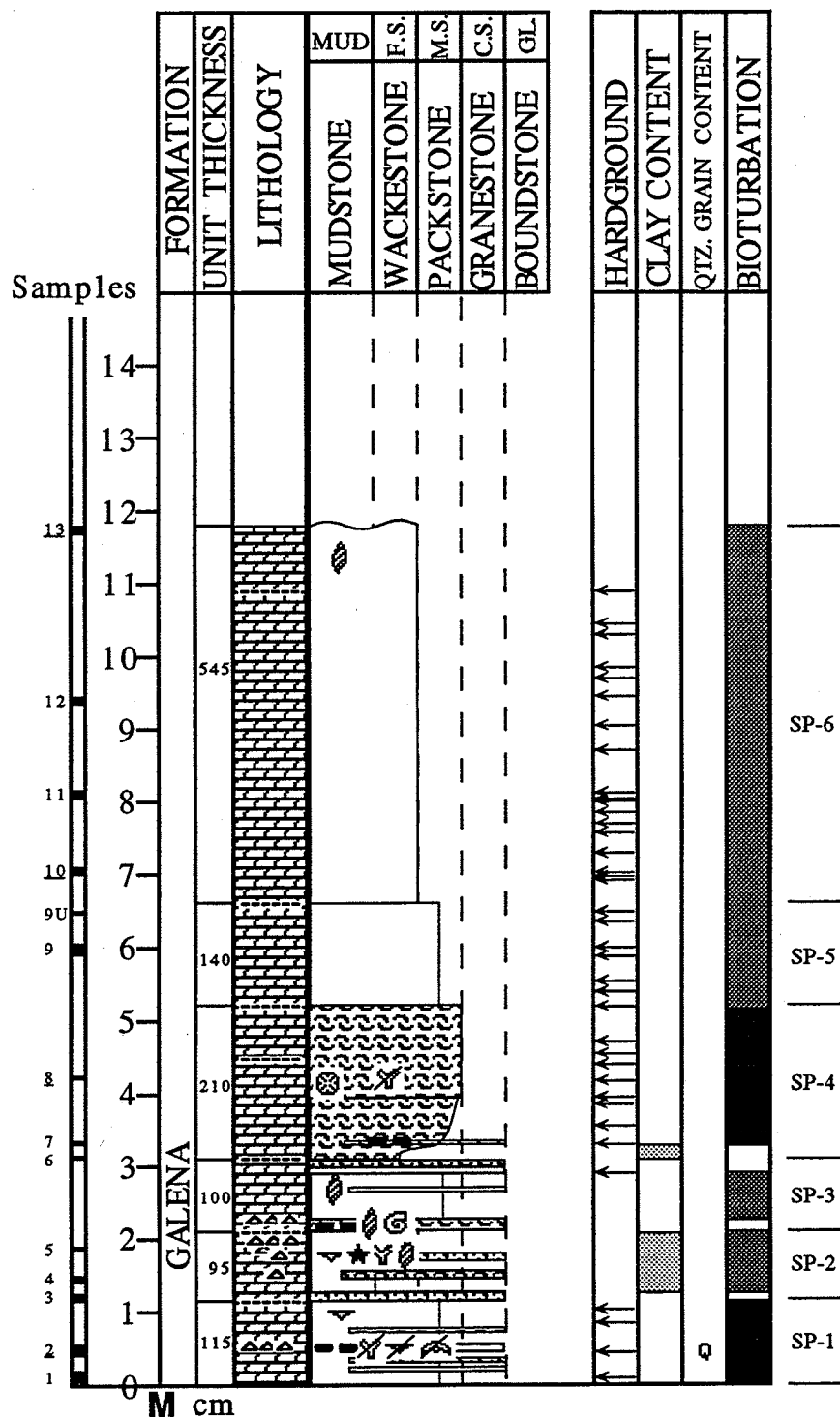


Fig. B-9. Columnar section measured from Spruce Qr., Locality 7. Descriptions of units followed next.

Description

Rock Unit No.
Top of section

SP-6

Dolostone, fine- to medium-crystalline, carbonate; light purplish gray on fresh beds to light brownish buff on weathered beds; thin-bedded; bioclastic wackestone; moderately bioturbated with 1-5 mm size burrows, some burrows are filled with shaly material; calcite spar patches of 3-4 cm size are abundant in lower part; vesicular porosity common, gastropod molds present in upper part; contains abundant hardgrounds; quartz silts present. (SP13,12,11,10)

SP-5

Dolostone, fine- to medium-crystalline, carbonate; light purplish gray to yellowish brown on weathered horizon; medium-bedded; bioclastic packstone to wackestone, gradually less grainy upward; moderately bioturbated with variable sized burrows up to 2 cm in diameter; calcite spar patches present; contains abundant hardgrounds; a prominent shaly parting at bottom; quartz silts present. (SP9U,9)

SP-4

Dolostone, fine- to medium-crystalline, argillaceous-free except basal portion; purplish brown on fresh surfaces; medium-bedded, gradually thicker bedded upward; bioclastic wackestone to packstone with some intercalating grainstone, black intraclastic pebbles are present in some grainstone beds; some brachiopod fragments are replaced by silica; moderately to strongly bioturbated; contains many hardgrounds; a prominent shaly parting at bottom; quartz silts present. (SP8,7,6)

SP-3

Dolostone, fine- to medium-crystalline; argillaceous-free with thin argillaceous partings; purplish brown; thin- to medium-bedded; white chert nodules present at lowermost part of the unit; bioclastic wackestone to packstone with occasionally intercalating grainstone lenses; gastropods abundant, cephalopods present; vesicular pores and gastropod molds common, 2-3 cm calcite spar patches common; weakly to moderately bioturbated with *Chondrites* burrows on bedding plains; contains hardgrounds.

SP-2

Dolostone, fine-crystalline, argillaceous; thin-bedded with irregular shaly partings; contains white chert nodules locally; light purplish brown; fossiliferous mudstone with grainstone lenses locally; moderately bioturbated; brachiopods, gastropods, crinoids, and bryozoans common; grainstone beds contain abundant moldic pores; locally calcite spar patches present. (SP5,4,3)

SP-1

Dolostone, fine- to medium-crystalline; contains white chert nodules; light purplish brown; thin- to medium-bedded with irregular thin gray shaly partings; moderate to strongly bioturbated with abundant *Chondrites* burrows on bedding plains, burrows are 2-4 mm in diameter; bioclastic wackestone to packstone with many intercalating grainstone beds; some grainstone beds contain black intraclasts; bioclasts consists of skeletal fragments

of bryozoans, brachiopods, and trilobites; quartz silts present; contains many ferruginous hardgrounds.
(SP2,1)

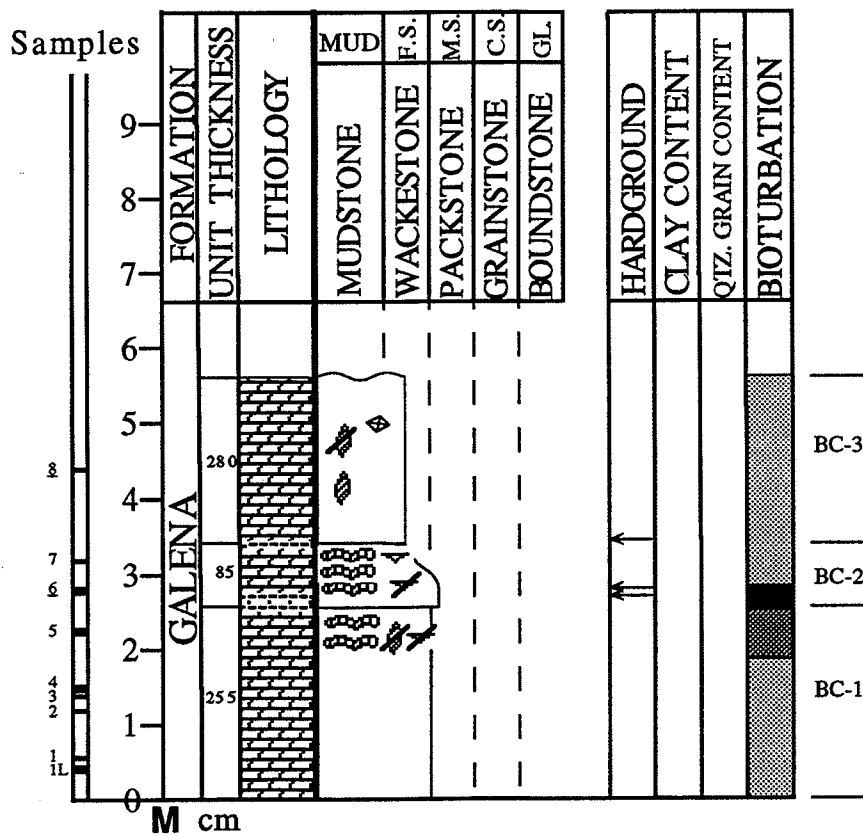


Fig. B-10. Columnar section measured from Buckhorn Corner Qr., Locality 8. Descriptions of units followed next.

Description

Rock Unit No.
Top of section

BC-3

Dolostone, fine-crystalline, carbonate; light purplish gray to light brownish buff; medium-bedded; fossiliferous mudstone to wackestone; weakly to moderately bioturbated with 1-4 mm-sized burrows; gastropod (?) moldic to vuggy porosity common on weathered surfaces; some are filled with large calcite spars; vesicular porosity common.

(BC8)

BC-2

Dolostone, fine-crystalline, carbonate; light purplish gray to buff; medium-bedded; bioclastic wackestone; moderately to strongly bioturbated with burrows of up to 1 cm in diameter, some burrows are filled with shaly material; contains abundant receptaculites and hardgrounds.

(BC6,7)

BC-1

Dolostone, fine-crystalline, carbonate to slightly argillaceous; light purplish brown to light yellowish brown on weathered horizon; medium-bedded; bioclastic wackestone; moderately to strongly bioturbated with small burrows, 1-5 mm in diameter; some burrows are filled with finer (shaly?) material; upper portion contains pyrite inside of large pores, 3-4 cm size; receptaculites and gastropod (?) moldic porosity common on weathered surfaces.

(BC,5,4,3,2,1)

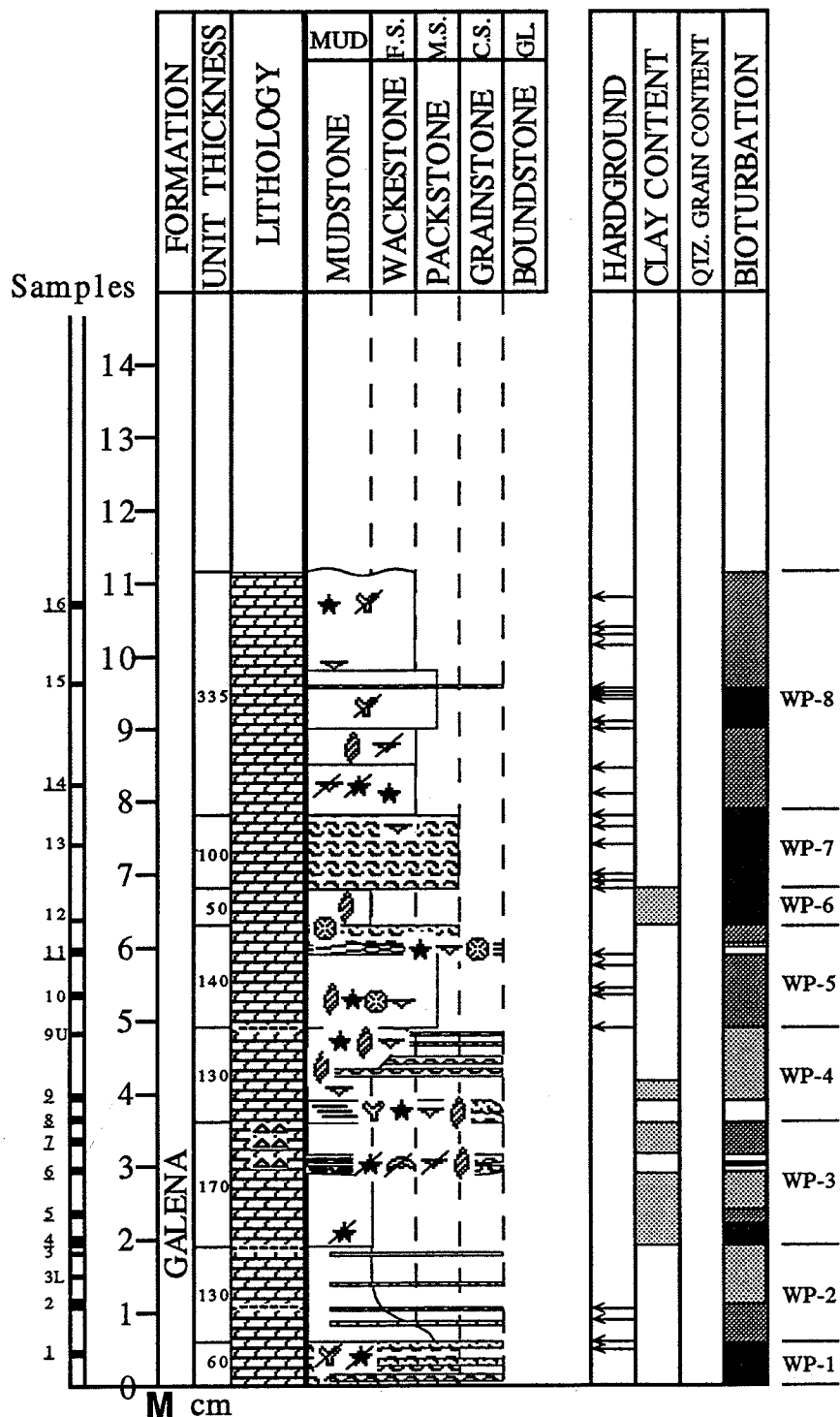


Fig. B-11. Columnar section of the Sinnipee Group in Waupun Qr., Locality 9. Descriptions of units followed next.

Description

Rock Unit No.
Top of section

WP-8

Dolostone, fine- to medium-crystalline, carbonate; light brownish buff; medium-bedded; fossiliferous mudstone to bioclastic wackestone; moderately bioturbated by 1-3 mm size burrows, burrows are filled with finer material; bryozoan (?) moldic to vuggy pores are abundant in the middle on weathered surfaces; some are filled with sparry calcite; vesicular porosity common in lower part; contains abundant hardgrounds; similar to SP-6.
(WP16,15,14)

WP-7

Dolostone, fine- to medium-crystalline, carbonate; light purplish gray; thin- to medium-bedded; bioclastic wackestone to packstone, gradually less grainy upward; moderately to strongly bioturbated by variable-sized burrows up to 1 cm in diameter; brachiopod moldic pores common; contains hardgrounds; similar to SP-5.
(WP13)

WP-6

Dolostone, fine-crystalline, slightly argillaceous; light buff to light gray; thin- to medium-bedded; mudstone; moderately to strongly bioturbated with 1-4 mm wide burrows.
(WP12)

WP-5

Dolostone, fine- to medium-crystalline, carbonate; light purplish gray to yellowish brown; medium- to thick-bedded; bioclastic mudstone to packstone with intercalating grainstone beds; moderately bioturbated by 1-3 mm-sized burrows; gastropods, orthid brachiopods common, crinoid present; contains hardgrounds.
(WP11,10)

WP-4

Dolostone, fine- to medium-crystalline; light purplish gray to brown; medium-bedded with thin shaly partings; fossiliferous mudstones interbedded with grainstones; weakly bioturbated; trepostome bryozoans, crinoids, orthid brachiopods, and gastropods (*Hormotoma major*) are common fossils; some brachiopod fragments are replaced by silica; quartz silts present.
(WP9U,9,8)

WP-3

Dolostone, fine-crystalline, argillaceous; light purplish gray; thin-bedded with thin irregular gray shaly partings; contains irregular white chert nodules in upper part; weak to strongly bioturbated by 1-6 mm-sized Chondrites burrows; fossiliferous mudstones with intercalating lenticular grainstone beds, some grainstone beds contain black intraclasts; some brachiopod fragments are replaced by silica while gastropods by clean spar.
(WP7,6,5,4)

WP-2

Dolostone, fine- to medium-crystalline; light purplish gray; thin- to medium-bedded with thin argillaceous partings; weakly to moderately bioturbated mostly by horizontal burrows 1-6 mm in diameter; mudstone with occasionally intercalating thin grainstone beds 1-5 cm

thick; gradually less bioturbated and finer crystalline upward containing less grainstone beds.

(WP3,3L,2)

WP-1

Dolostone, medium-crystalline; light gray; medium-bedded; moderately to strongly bioturbated, burrows are variable in size up to 1 cm in diameter; bioclastic wackestone to packstone interbedded with grainstone; contains bryozoans and crinoids and minor quartz silts; contains hardgrounds.

(WP1)

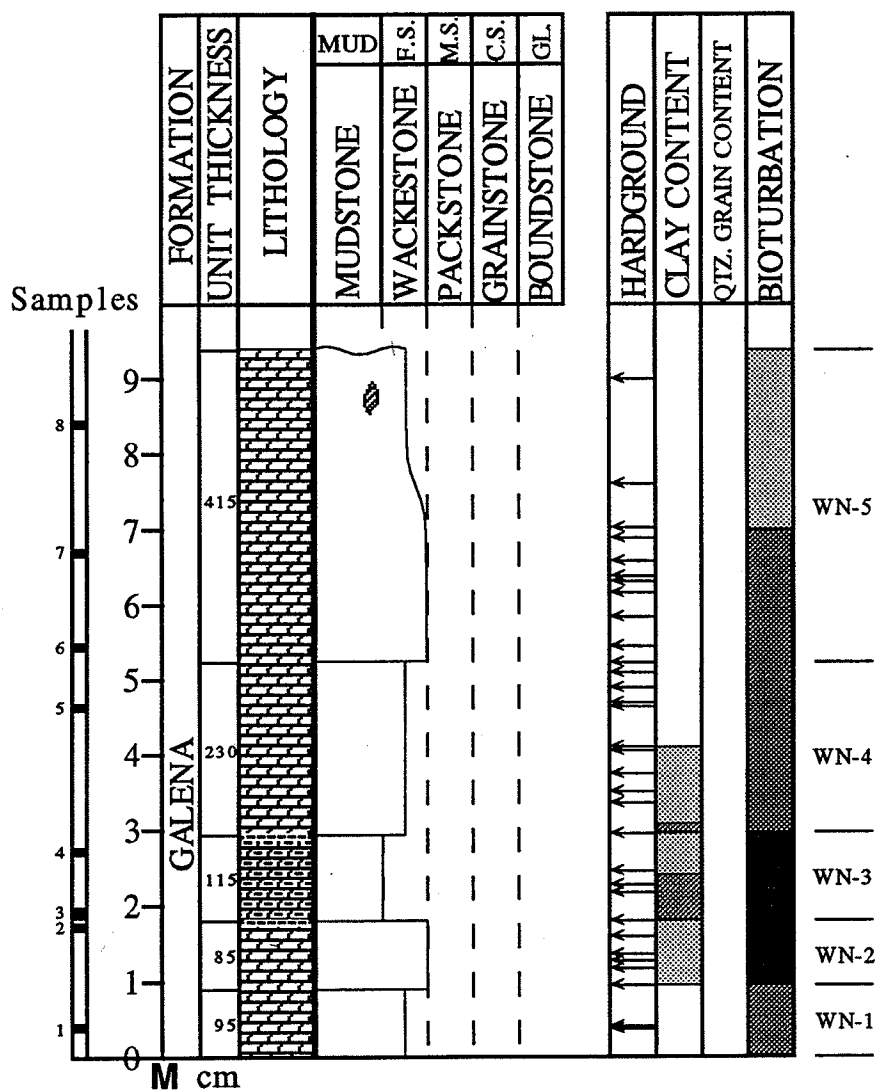


Fig. B-12. Columnar section measured from Waupun North Qr., Locality 10. Descriptions of units followed next.

Description

Rock Unit No.
Top of section

WN-5

Dolostone, fine-crystalline, less argillaceous than below; light purplish gray to buff yellow; medium-bedded; bioclastic wackestone to packstone with thin intercalating grainstone beds; moderately to strongly bioturbated by 1-3 mm-wide burrows and larger 1-2 cm-wide burrows; gastropods, brachiopods common; contains hardgrounds.
(WN8,7,6)

WN-4

Dolostone, fine-crystalline; light purplish brown; medium-bedded with thin shaly partings; fossiliferous mudstone; moderately to strongly bioturbated; contains hardgrounds.
(WN5)

WN-3

Dolostone, fine-crystalline; argillaceous; greenish gray; medium-bedded fossiliferous mudstone with very thin (<1 cm) calcarenite beds; gradually less argillaceous and thicker bedded upward with a prominent shaly parting at base; moderately to strongly bioturbated; contains abundant hardgrounds.
(WN4,3)

WN-2

Dolostone, fine-crystalline; light purplish gray to greenish gray; medium-bedded with thin irregular shaly partings; moderately to strongly bioturbated by 1-4 mm-sized burrows; fossiliferous mudstone to wackestone; contains abundant hardgrounds.
(WN2)

WN-1

Dolostone, fine- to medium-crystalline; light purplish brown; medium-bedded; weakly to moderately bioturbated with abundant horizontal burrows on bedding plains, burrows are variable in size up to 2 cm in diameter; fossiliferous mudstone to wackestone with thin packstone to grainstone lenses; contains hardgrounds.
(WN1)

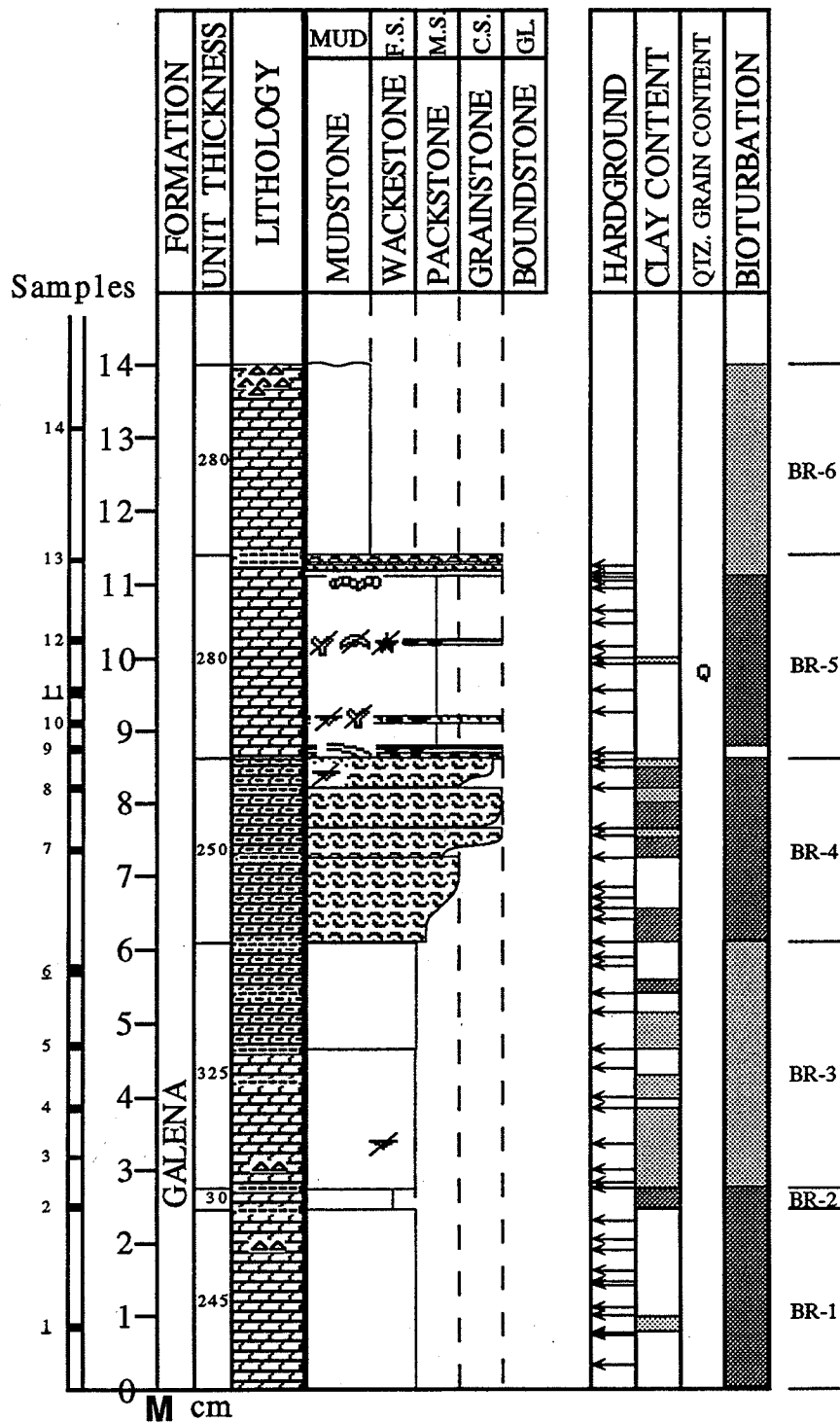


Fig. B-13. Columnar section measured from Brandon Qr., Locality 11. Descriptions of the units followed next

Description**Rock Unit No.**
Top of section**BR-6**

Dolostone, fine-crystalline, carbonate; light purplish gray to brown; thin- and irregular-bedded; weakly bioturbated; mudstone; contains chert nodules in the upper part.
(BR14)

BR-5

Dolostone, medium- to coarse-crystalline, carbonate; light purplish gray; medium-bedded; bioclastic mudstone to packstone with intercalating grainstone beds containing brachiopods, bryozoans, and trilobites; moderately bioturbated; contains abundant hardgrounds and black pebbles derived from them; brachiopod molds present; bounded above by 0.5 cm thick green shale laminae; contains abundant quartz silts at lower part.
(BR13,12,11,10,9)

BR-4

Dolostone, medium-crystalline; argillaceous-free, skeletal grainstone to packstone interbedded with argillaceous wackestone to packstone; greenish gray in argillaceous beds while purplish brown in carbonate beds; gradually more argillaceous upward; four upward argillaceous-free sequences are defined with gradually thicker bedded upward trend within each sequences; medium-bedded; moderately bioturbated by 1 cm-sized burrows; contains abundant hardgrounds of which burrows are filled with overlying lithology; contains terrigenous silts of up to 20%.
(BR8,7)

BR-3

Dolostone, medium-crystalline, carbonate to argillaceous; locally white chert nodules present; light purplish brown; medium-bedded; fossiliferous mudstone to wackestone; weakly to moderately bioturbated; brachiopods common; contains hardgrounds in 40 cm interval.
(BR6,5,4,3)

BR-2

Dolostone, medium-crystalline, argillaceous; purplish gray to greenish yellow; thin-bedded; fossiliferous mudstone to wackestone; moderately to strongly bioturbated by burrows filled with green shaly material, gradually less argillaceous upward; bounded above by a prominent argillaceous laminae, 1 cm thick.
(BR2)

BR-1

Dolostone, medium-crystalline carbonate; light purplish gray; medium-bedded with thin green shaly partings; texture is hard to identify due to dolomitization, bioclastic wackestone with terrigenous silts less than 1%; moderately bioturbated with 1-2 cm thick, mottled burrows and 1-3 mm-sized burrows; calcite spar patches present; contains abundant hardgrounds.
(BR1)

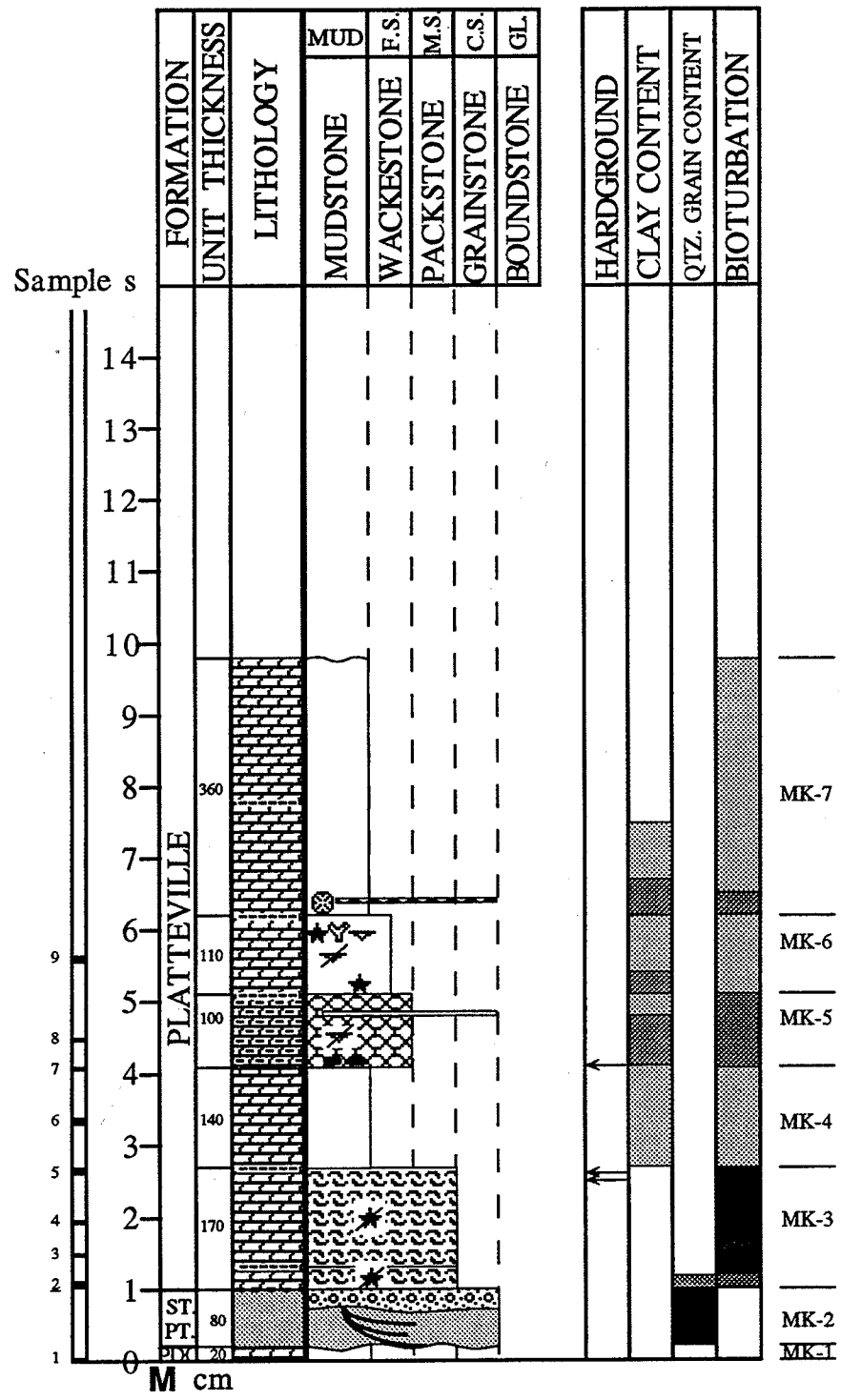


Fig. B-14. Columnar section measured Markesan Qr., Locality 12. Descriptions of units followed next.

Description

Rock Unit No.

Top of section

MK-7

Dolostone, very fine-crystalline, argillaceous; thin- to medium-bedded; gradually less argillaceous upward; light purplish gray to buff yellow; mudstone; contains thin bioclastic grainstone lenses; weakly bioturbated except bottom portion.

MK-6

Dolostone, fine-crystalline, argillaceous; light purplish gray; thin- to medium-bedded; gradually less argillaceous upward; fossiliferous mudstone to wackestone; weakly bioturbated.

(MK9)

MK-5

Dolostone, fine-crystalline; argillaceous; thin-bedded with irregular argillaceous seams showing nodular appearance; gradually finer crystalline, less argillaceous, less grainy, and thicker bedded upward; light purplish gray to greenish gray; moderately bioturbated; fossiliferous mudstone to wackestone with occasional thin intercalating grainstones; contains brachiopods; 7 cm-sized bored intraclasts present at 10 cm above the hardground.

(MK8)

MK-4

Dolostone, very fine-crystalline; argillaceous; thin- to medium-bedded with 0.5-1 cm-thick argillaceous partings; medium gray; weakly to moderately bioturbated with 2-7 mm-sized dark gray mottled burrows; mudstone; similar to RP-5 but a little more bioturbated and argillaceous; a very sharp hardground on top of the unit.

(MK7,6)

MK-3

Dolostone, fine- to medium-crystalline, carbonate; medium-bedded; strongly to pervasively bioturbated with burrows, 2-6 mm in diameter, gradually more bioturbated upward; medium gray to buff; crinoidal wackestone to packstone; bounded above by a prominent shaly parting; contains a 2 cm-thick green laminated shale horizon, 20 cm above the base; similar to RP-4 but quartz grains are rare; contains hardgrounds in the upper part.

(MK5,4,3,2)

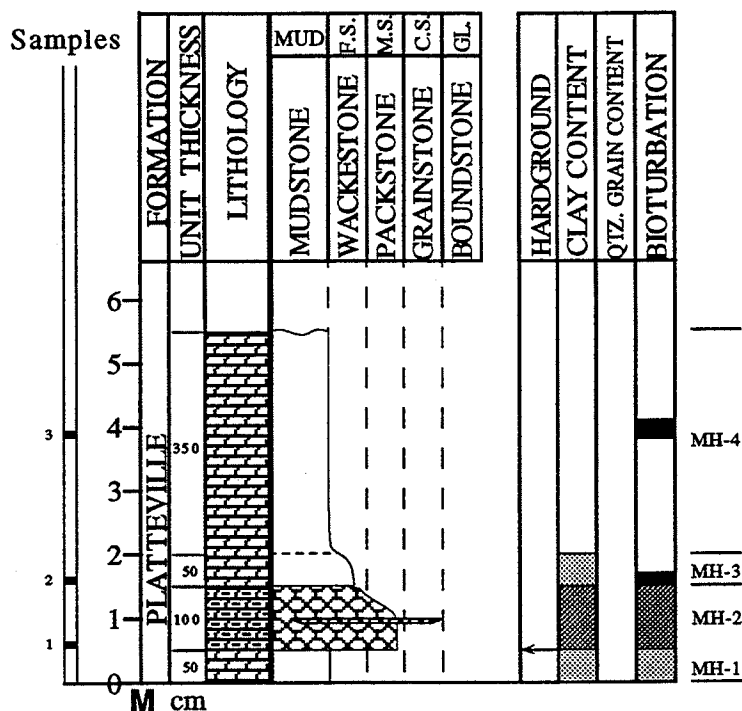
MK-2

Sandstone, massive; medium- to coarse-grained, very well-rounded quartz grains; thick-bedded; light yellow; have undulating lower contact and flat upper contact; both boundaries are Fe-mineralized.

MK-1

Dolostone, very fine-crystalline, carbonate; medium-bedded; buff yellow; mudstone.

(MK1)



Description

Rock Unit No.
Top of section

MH - 4

Dolostone, very fine-crystalline; argillaceous, gradually less argillaceous upward; buff yellow; thin- to medium-bedded mudstone with thin bioclastic grainstone lenses; mostly weakly bioturbated but some beds are strongly bioturbated with 3-5 mm-sized burrows.

MH - 3

Dolostone, fine-crystalline; thin- to medium-bedded; gradually less argillaceous upward; fossiliferous mudstone to wackestone; moderately to strongly bioturbated; brachiopods abundant.

(MH2)

MH - 2

Dolostone, fine-crystalline; argillaceous; thin-bedded with irregular argillaceous partings showing nodular appearance; gradually less argillaceous, less grainy, and thicker bedded upward; buff yellow due to weathering; moderately bioturbated; bioclastic wackestone to packstone; contains brachiopod molds.

(MH1)

MH - 1

Dolostone, very fine-crystalline; argillaceous; buff color due to weathering; planar, thin- to medium-bedded; medium grey; weakly to moderately bioturbated with 2-5 mm-sized horizontal burrows; mudstone; similar to MK-4; a very sharp hardground on top of the unit.

Fig. B-15. Columnar section measured from Mackford Hill, Locality 13.

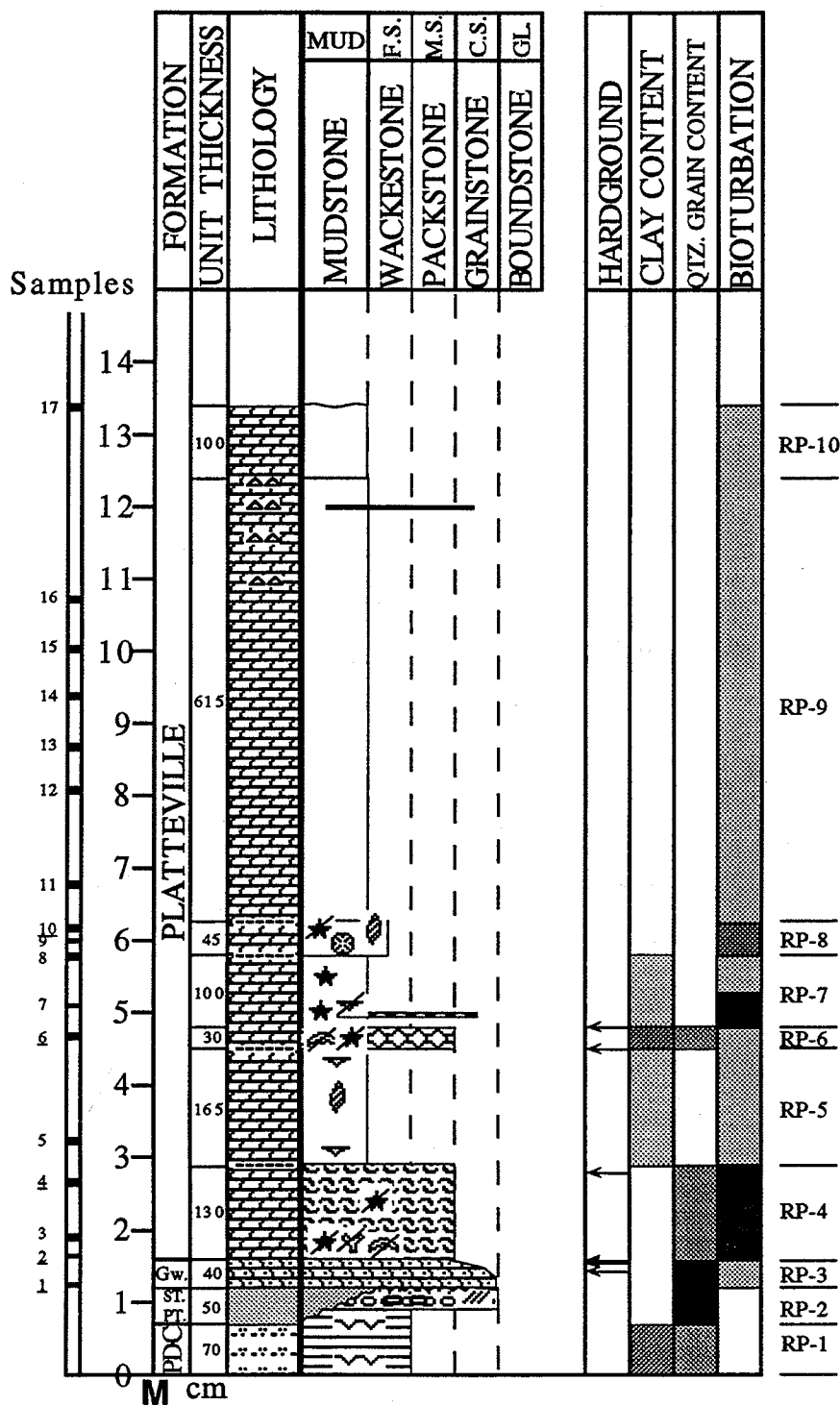


Fig. B-16. Columnar section measured from Ripon Qr., Locality 14. Descriptions of units followed next.

Description

Rock Unit No.

Top of section

RP-10

Dolostone, fine- to medium-crystalline; less argillaceous than below; medium-bedded; weakly bioturbated; mudstone.

(RP17)

RP-9

Dolostone, very fine-crystalline; argillaceous, gradually less argillaceous upward; contains locally white chert nodules, 2-5 cm-sized in short axis; the chert nodules are rounded, irregular, and laterally elongated up to 15 cm; medium-bedded with wavy argillaceous partings; light purplish gray to buff; slightly bioturbated mostly by horizontal burrows, 0.5 cm in diameter; mudstone; thin bioclastic grainstone lenses present in the upper part; shows conchoidal fracture.

(RP16,15,14,13,12,11)

RP-8

Dolostone, fine- to medium-crystalline, carbonate; thin- to medium-bedded; buff yellow; moderately to weakly bioturbated by 2-5 mm-wide burrows; less bioturbated, finer crystalline upward; contains solitary corals and gastropods.

(RP10,9)

RP-7

Dolostone, fine-crystalline, argillaceous; thin- to medium-bedded with wavy argillaceous partings in 2-4 cm interval; medium gray with dark gray mottling to buff yellow; moderately to strongly bioturbated by 2-5 mm-sized burrows; gradually less bioturbated, less argillaceous, coarser crystalline, thicker bedded upward; fossiliferous mudstone containing crinoid molds and brachiopods; Fe-mineral concentration inside of fossil molds.

(RP8,7)

RP-6

Dolostone, fine- to medium-crystalline, argillaceous; buff yellow to brown; medium-bedded; bioclastic packstone to grainstone with trilobites and crinoids; contains floating quartz sands 1% in proportion; bounded above and below by hardgrounds.

(RP6)

RP-5

Dolostone, very fine-crystalline, argillaceous; medium-bedded with 0.5-2 cm-thick wavy argillaceous partings; medium gray; weakly bioturbated with 3-9 mm-wide dark gray mottled burrows; fossiliferous mudstone containing brachiopods and gastropods; Fe-mineral concentration inside of burrows and/or fossil molds.

(RP5)

RP-4

Dolostone, fine- to medium-crystalline with floating quartz sands 1-5 % in proportion; medium-bedded with very thin argillaceous partings in 10-20 cm intervals; medium gray; strongly to pervasively bioturbated with 2-7 mm-wide burrows; gradually less sandy, finer grained, and more bioturbated upward; quartz sand grains are very well rounded, medium- to coarse-grained and more concentrated near by burrows; 0.2 mm-sized

phosphate grains common; crinoidal bioclastic wackestone to packstone with common bryozoans and trilobites; contains pyrite and sphalerite(?) concentration inside of moldic pores; bounded above by a 1 cm thick prominent argillaceous parting.
(RP4,3,2)

RP-3

Sandy dolostone to dolomitic sandstone; gradually less sandier upward; light to medium gray; weakly to moderately bioturbated with 0.5 cm-wide burrows, medium-bedded; the quartz grains are medium- to coarse-grained and well rounded; quartz grains comprise 50 % in proportion; contains and bounded above by ferruginous hardgrounds; 0.07-0.2 mm-sized phosphate grains common and particularly abundant inside of burrows; Fe-mineralization along the lower boundary.
(RP1)

RP-2

Quartz arenite, medium- to coarse-grained, well rounded; finely laminated and cross bedded, upper 30 cm interval is massive; gradually coarser grained upward.

RP-1

Dolostone, medium-crystalline, interbedded with green shale to sandy shale partings up to 1 cm thick; thin- to medium-bedded; contains mud cracks filled with (sandy) shale; uppermost part bed is an intraclastic, sandy conglomerate showing normal grading with cross-laminated top.

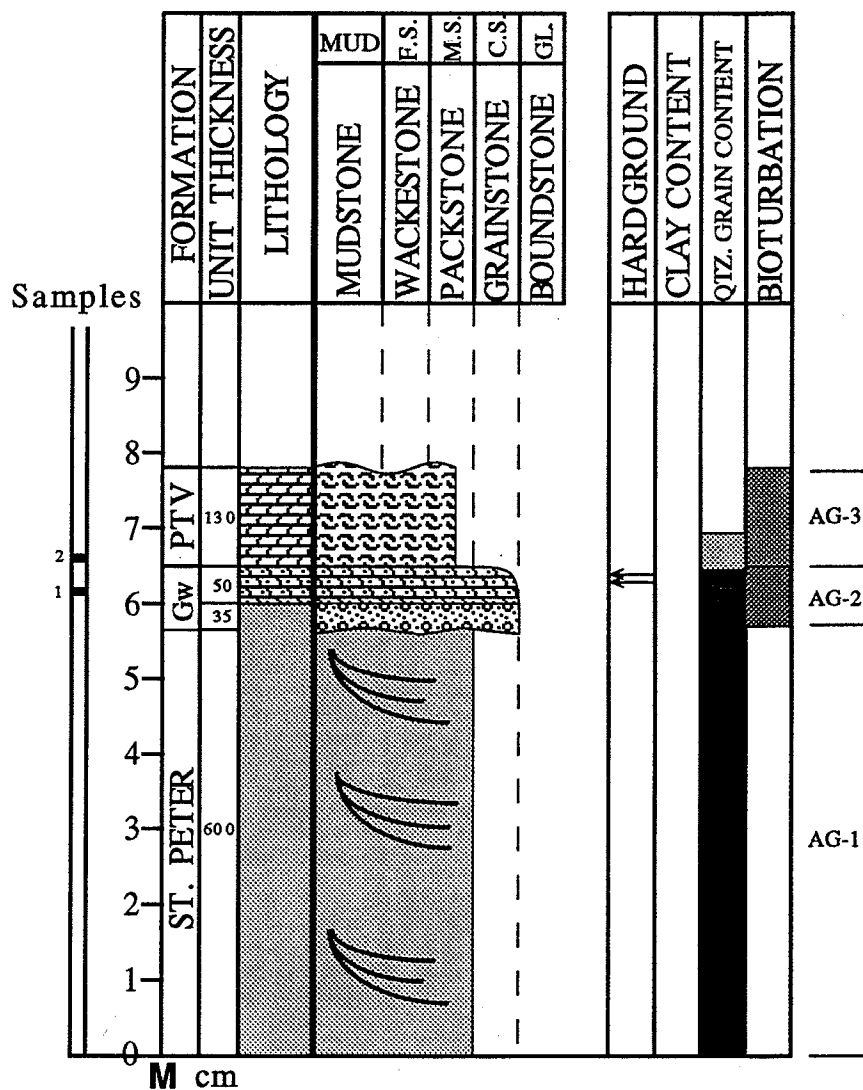


Fig. B-17. Columnar section measured from Arcade Glen, Locality 15. Descriptions of units followed next.

Description**Rock Unit No.****Top of section****AG-3**

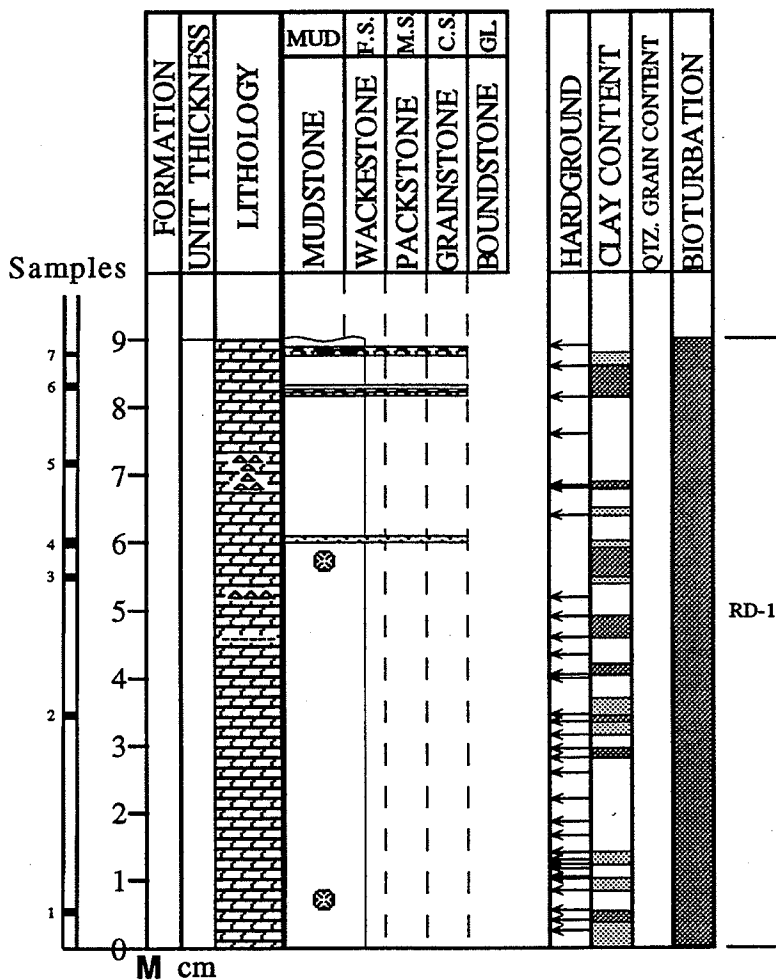
Dolostone, fine- to medium-crystalline with floating quartz sand grains; quartz grains are very well rounded, coarse-grained, more concentrated near by burrows, and gradually decrease upward in proportion; thin- to medium-bedded; buff yellow due to weathering; moderately to strongly bioturbated; fine to medium sand-sized phosphate grains common; bioclastic wackestone.

(AG2)**AG-2**

Sandy dolostone; sand grains are very well rounded, coarse-grained, and gradually decrease upward in proportion; buff yellow due to weathering; moderately bioturbated; contains hardgrounds; Fe mineralization along the lower boundary.

(AG1)**AG-1**

Quartz arenite, quartz grains are medium- to coarse-grained and well rounded; large scale cross-bedded and laminated; upper portion is massive and coarse-grained in size.



Description

Rock Unit No.
Top of section

RD-1

Dolostone, medium-crystalline; carbonate to argillaceous; white chert nodules present locally; medium- to thick-bedded; alternations of argillaceous-free, purplish brown beds and argillaceous, greenish gray beds; transitions from argillaceous bed to less argillaceous bed are mostly gradational unless interrupted by hardground whereas reverse cases are generally sharp; fossiliferous mudstone to wackestone with occasional intercalation of thin grainstone beds in the upper part; weakly to moderately bioturbated; contains many hardgrounds; hardgrounds are generally more prominent in case occurred between lithofacies boundaries. (RD7,6,5,4,3,2,1)

Fig. B-18. Columnar section measured from Rosandale Qr., Locality 16.

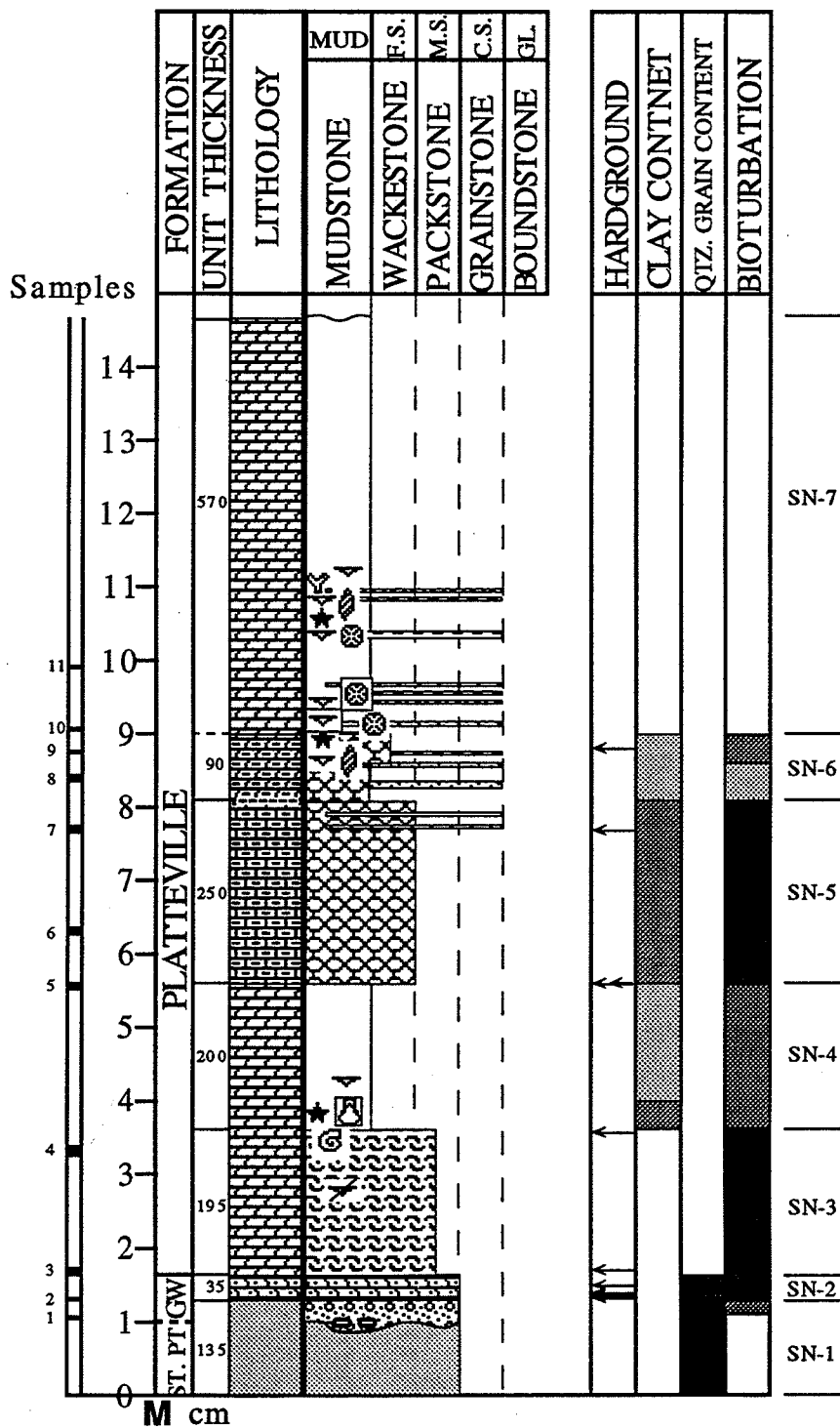


Fig. B-19. Columnar section measured from Sun Prairie Qr., Locality 17. Descriptions of units followed next.

Description

Rock Unit No.

Top of section

SN-7

Dolostone, very fine-crystalline; slightly argillaceous; thin-bedded mudstone; weakly bioturbated; less bioturbated and less argillaceous than lower unit; contains gastropods, brachiopods (*Campylorthis*), coral, bryozoans, and crinoids; upper parts are not described in detail due to inaccessibility.

(SN11,10)

SN-6

Dolostone, fine-crystalline, argillaceous; buff yellow; thin-bedded; moderately to strongly bioturbated; fossiliferous mudstone to wackestone with thin intercalating grainstone beds less than 5 cm thick; gastropods (*Clathrospira*) and brachiopods (*Rostricellula*) abundant; crinoids common.

(SN9,8)

SN-5

Limestone, very fine-crystalline; argillaceous; thin-bedded with irregular shale partings showing nodular appearances; greenish gray; moderately to strongly bioturbated with 2-3 cm-wide horizontal burrows; bioclastic wackestone with intercalating thin bioclastic grainstone beds; brachiopods, crinoids common; contains hardgrounds.

(SN7,6)

SN-4

Dolostone, very fine-crystalline; argillaceous; medium-bedded; moderately bioturbated; gradually thicker bedded and less argillaceous upward; purplish brown with dark gray mottlings, 2-5 mm in diameter; fossiliferous mudstone; two prominent, closely spaced hardgrounds on top.

(SN5)

SN-3

Dolostone, medium-crystalline, carbonate; medium to dark gray; medium- to thick-bedded; bioclastic wackestone to packstone; strongly to pervasively bioturbated with 3-5 mm-wide burrows; brachiopods molds abundant; cephalopod molds present;

(SN4,3)

SN-2

Sandy dolostone to dolomitic sandstone; contains poorly-sorted quartz sands grains in dolomite matrix; quartz grains comprise 50% in proportion; light yellow; medium-bedded; hardgrounds common.

(SN2)

SN-1

Quartz arenite, fine- to coarse-grained, moderately to poorly sorted; yellowish-brown; massive; irregular iron mineralization in uppermost part; contains few gravels of oolitic grainstone in the upper part; sedimentary structures are not recognizable due to poor exposure.

(SN1)

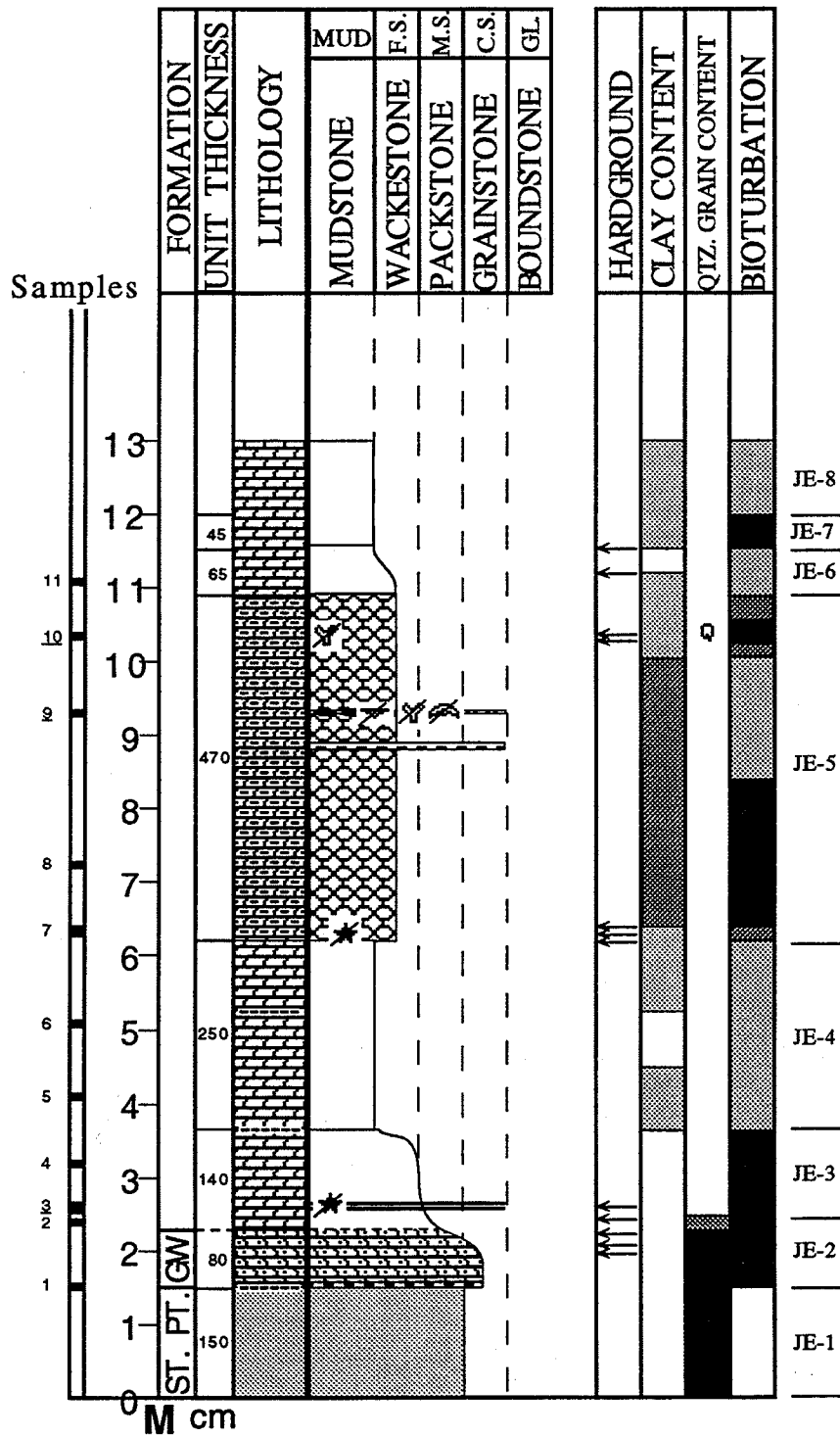


Fig. B-20. Columnar section measured from core, Locality JE. Descriptions of units followed next.

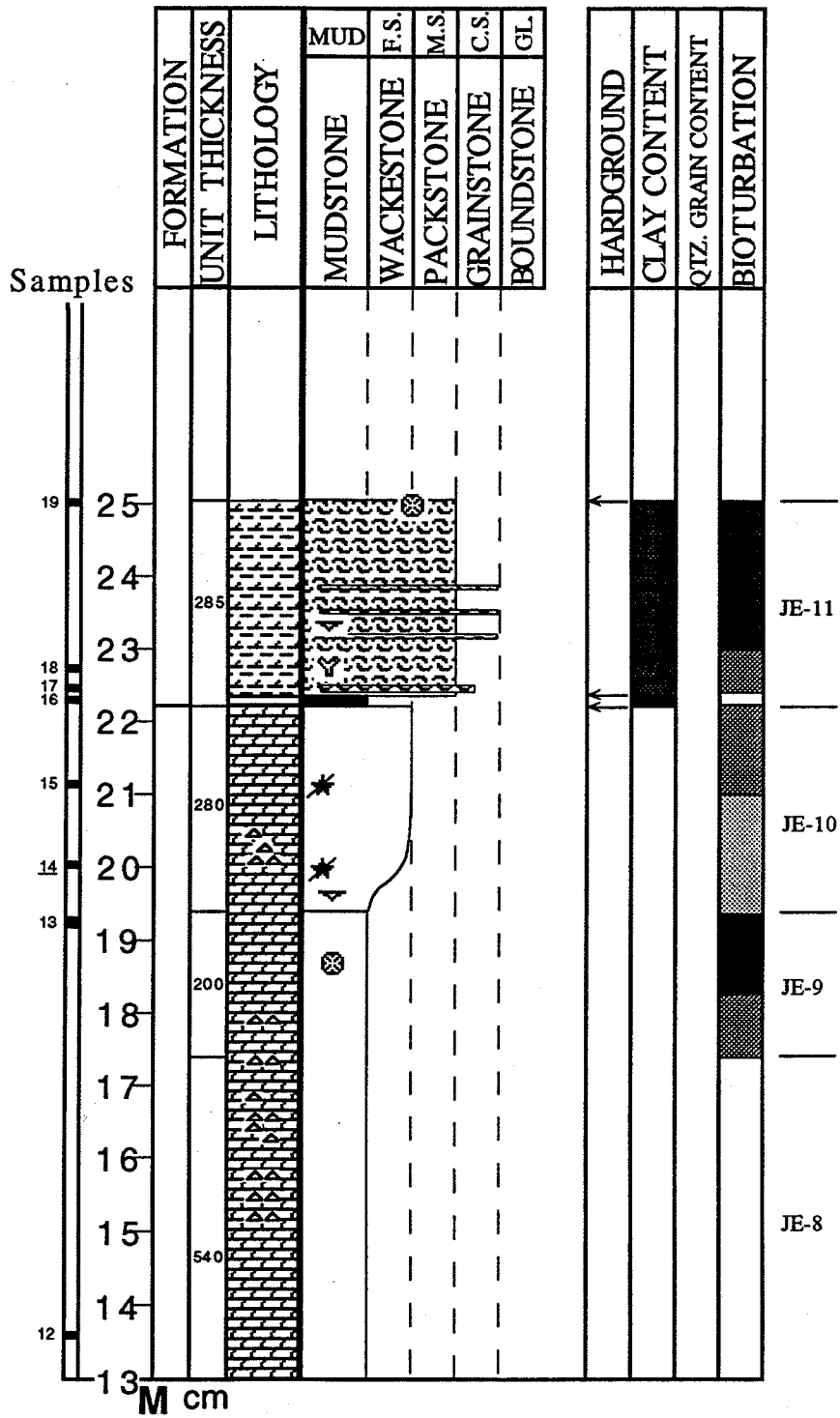


Fig. B-20. continued.

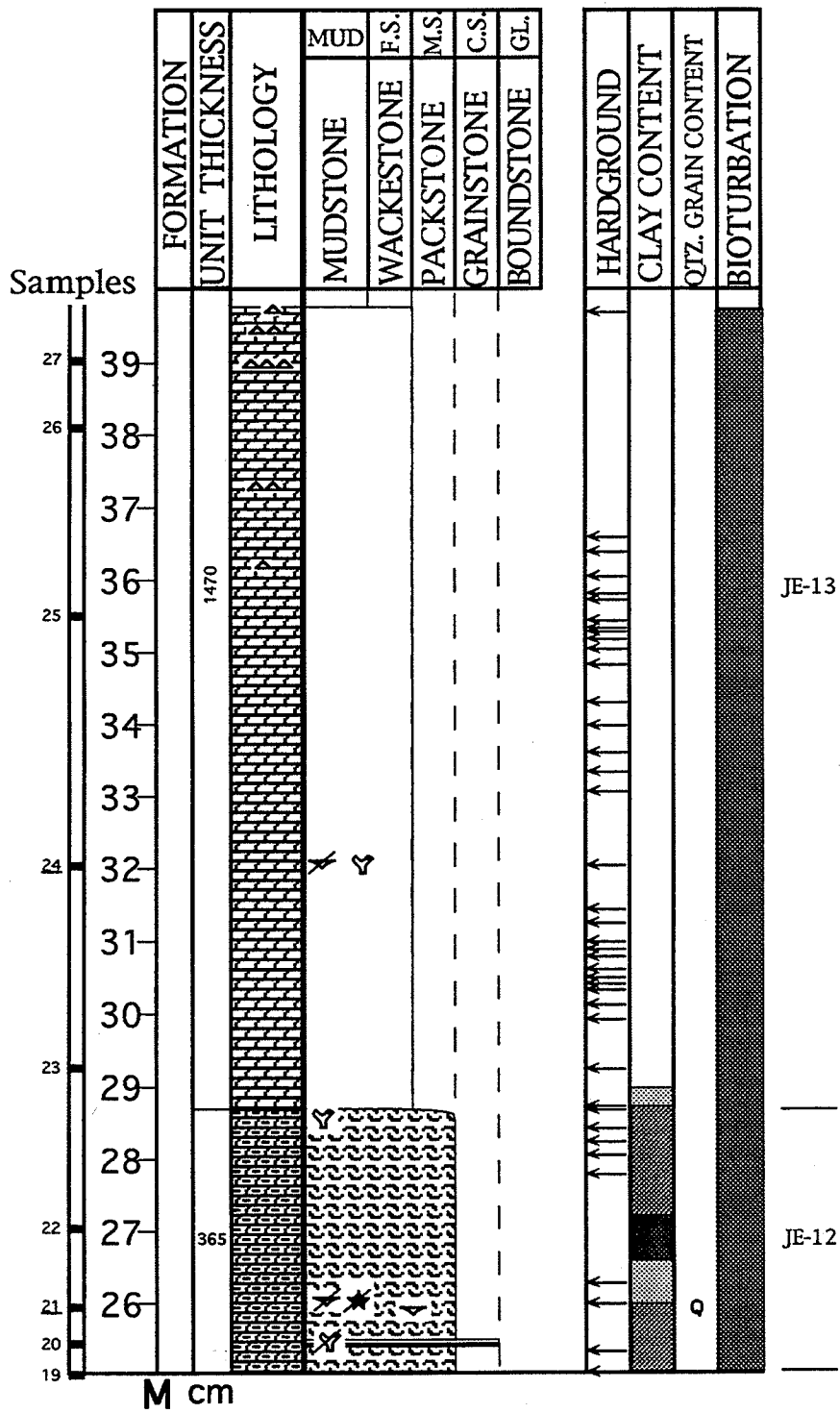


Fig. B-20. continued.

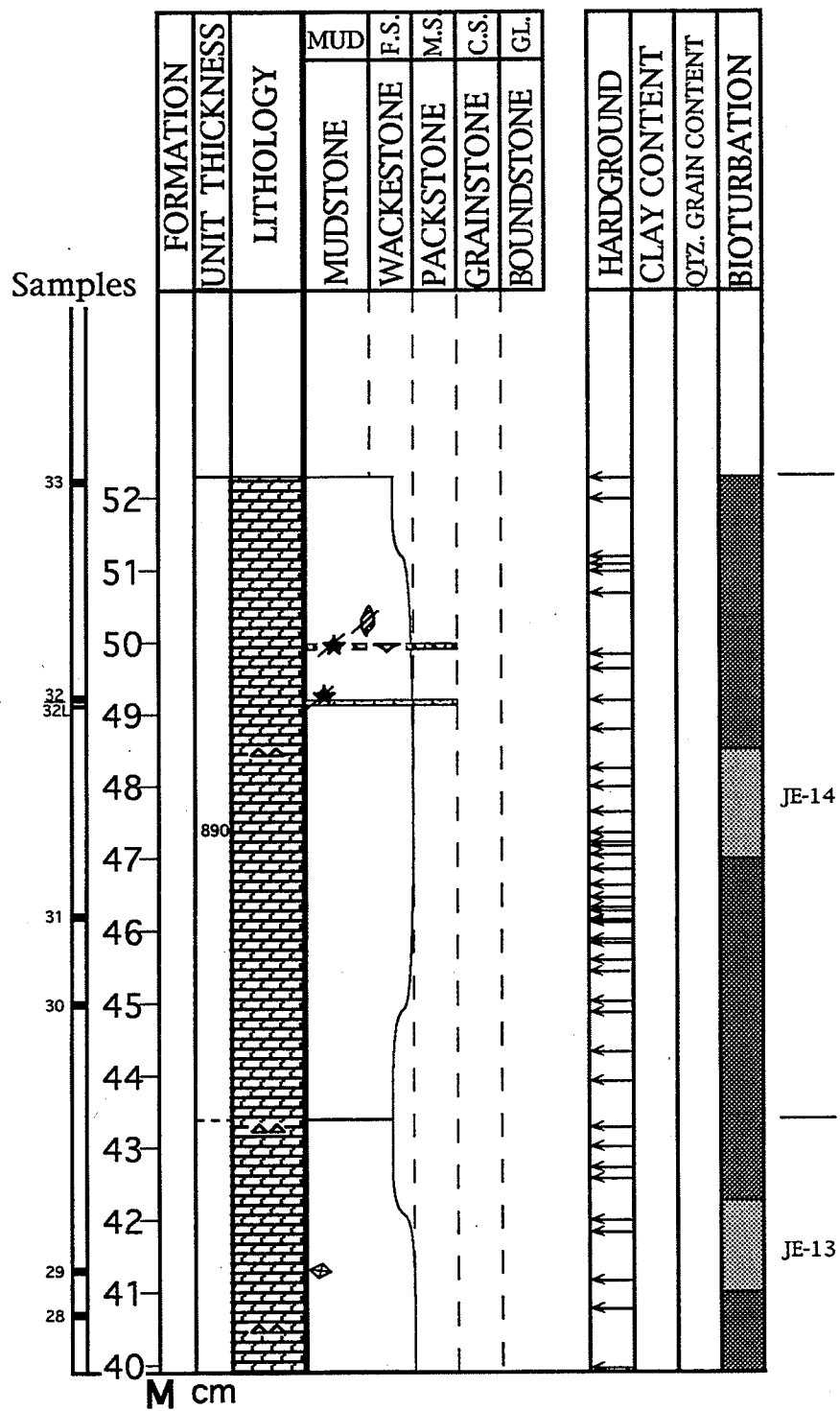


Fig. B-20. continued.

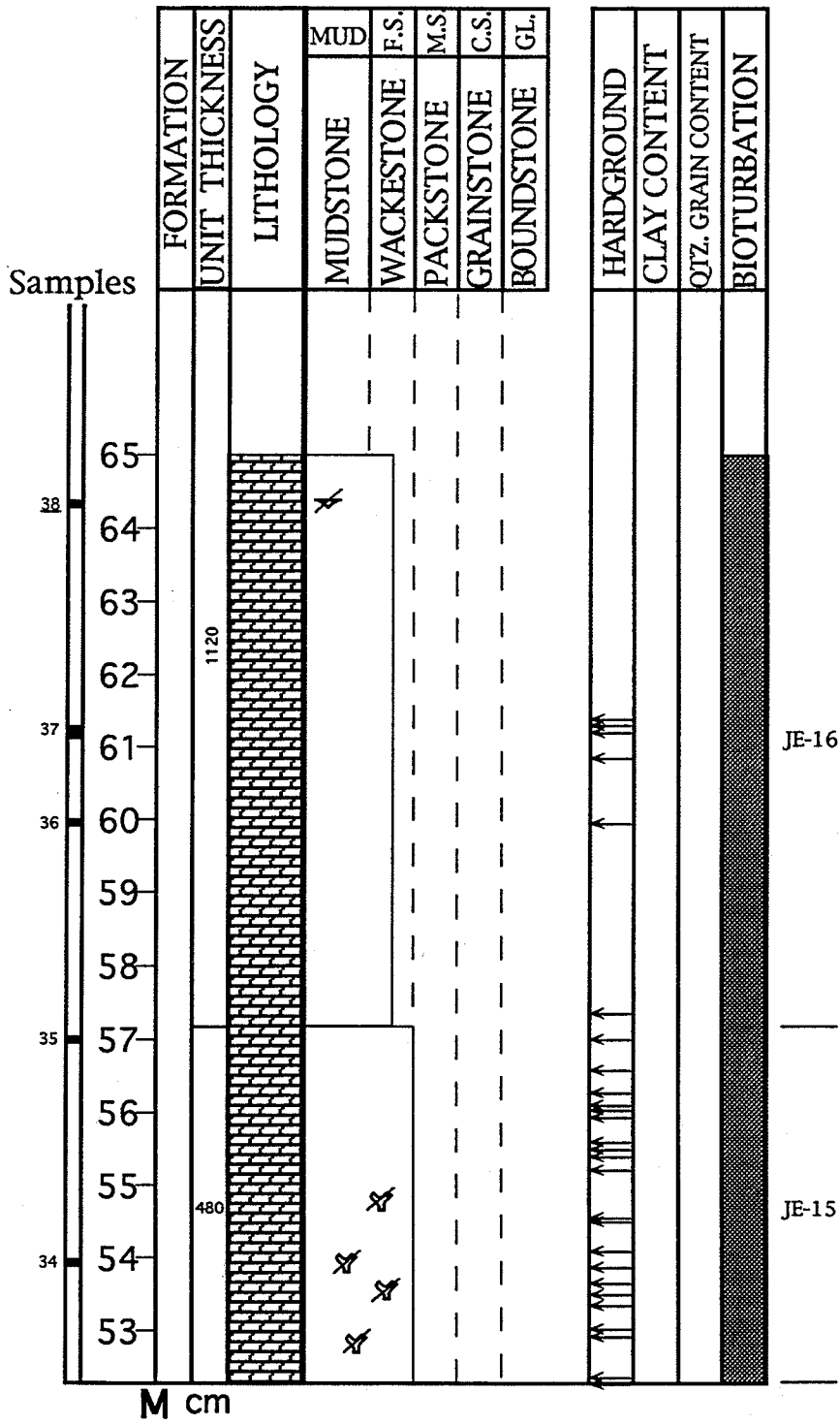


Fig. B-20. continued.

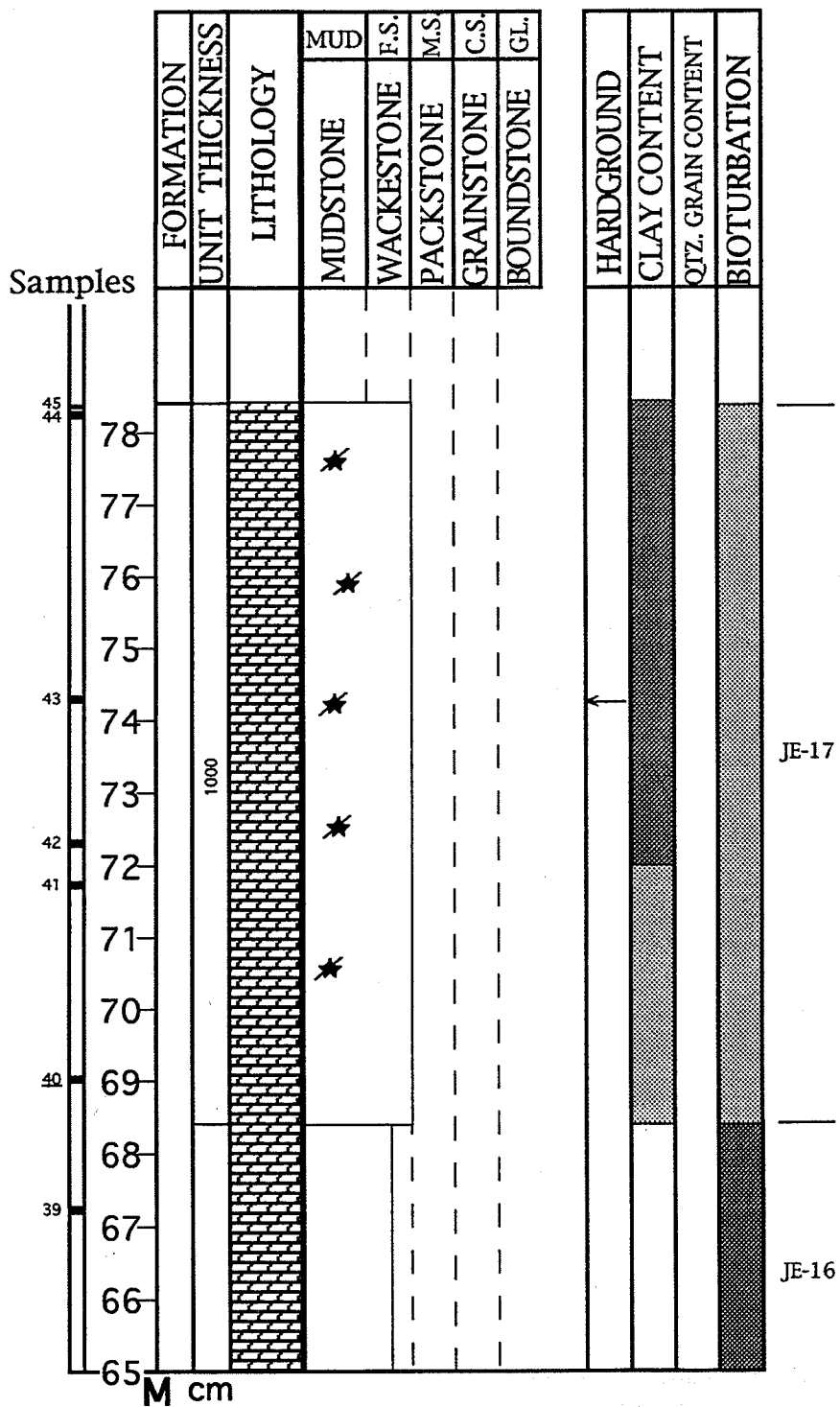


Fig. B-20. continued.

Description

Rock Unit No.

Top of section

JE-17

Dolostone, fine-crystalline, slightly to moderately argillaceous with dark brown argillaceous partings rich in phosphate grains; light yellowish brown; crinoidal wackestone with occasionally intercalating packstone beds; weakly bioturbated.

(JE45,44,43,42,41,40)

JE-16

Dolostone, fine-crystalline, carbonate; light brown; fossiliferous mudstone to wackestone; locally abundant vuggy pores associated with bryozoans; hardgrounds present locally; moderately bioturbated.

(JE39,38,37,36)

JE-15

Dolostone, medium-crystalline, carbonate; light brown; bioclastic wackestone; locally abundant vuggy pores associated with bryozoans; hardgrounds abundant; moderately bioturbated.

(JE35,34)

JE-14

Dolostone, fine- to medium-crystalline, carbonate; light brown to light yellowish brown; bioclastic wackestone with occasionally intercalating thin-bedded bioclastic packstone to grainstone beds; crinoids and brachiopods common, gastropod molds present; weakly to moderately bioturbated; contains abundant hardgrounds associated with *Thalassinoides* burrows.

(JE33,32,32L,31,30)

JE-13

Dolostone, medium-crystalline, carbonate; gradually less argillaceous upward; light brown with greenish tint in the lower part; bioclastic wackestone (?); white chert nodules abundant locally; contains abundant hardgrounds and vesicular to moldic porosities; weakly to moderately bioturbated; brachiopod and bryozoan molds common.

(JE29,28,27,26,25,24,23)

JE-12

Dolostone, medium-crystalline, moderately to very argillaceous; greenish gray; bioclastic packstone to grainstone mixed with clay due to bioturbation; less argillaceous than the unit below; rich in trepostome bryozoans; some grainstone beds show low angle cross lamination; weakly bioturbated; terrigenous silts present; hardgrounds common.

(JE22,21,20,19)

JE-11

Dolostone, medium-crystalline, shaly to shale; green; shaly bioclastic packstone with intercalating grainstone beds; shaly material occur as burrow fillings as well as mm-thick partings between beds; some grainstone beds are laminated; moderately to strongly bioturbated by 2-5 mm-wide burrows filled with shale; brachiopods and trepostome bryozoans abundant, corals present; bounded above by a prominent hardground.

(JE19,18,17,16)

JE-10

Dolostone, fine- to medium-crystalline; light brown; white chert nodules abundant in the lower part; irregularly distributed vesicular to vuggy pores; fossiliferous mudstone to wackestone; contains brachiopod molds and crinoids; porosity increases upward; weakly to moderately bioturbated; terrigenous silts present in less than 1 % proportion; occasionally lamination observed within chert nodules; a very prominent hardground present on top of the unit.

(JE15,14)

JE-9

Dolostone, fine- to medium-crystalline, slightly argillaceous; moderately to pervasively bioturbated by 2-5 mm-wide *Chondrites* burrows; gradually more bioturbated upward; mudstone; very thin (<1 cm) bioclastic grainstone lenses present locally.

(JE13)

JE-8

Dolostone, very fine-crystalline, slightly argillaceous to carbonate; gradually less argillaceous upward; brown to tan; contains locally white chert nodules in the upper part; the chert nodules are rounded and laterally elongated and are 2-5 cm-sized in short axis; slightly bioturbated mostly by horizontal burrows, less than 0.5 cm in diameter; mudstone.

(JE12)

JE-7

Dolostone, fine- to medium-crystalline, slightly argillaceous; medium gray; strongly bioturbated by 2-5 mm-wide, dark gray mottled burrows; mudstone.

JE-6

Dolostone, very fine- to fine-crystalline, carbonate; light purplish gray; weakly bioturbated by 2-5 mm-wide dark gray burrows; mudstone; contains irregularly distributed vesicular pores.

(JE11)

JE-5

Dolostone, fine- to medium-crystalline, moderately to very argillaceous with 0.5-1 cm-thick argillaceous seams; gradually less argillaceous upward in the upper part; greenish gray to light brownish gray; fossiliferous mudstone to wackestone with occasional thin-bedded grainstone beds, less than 5 cm thick; moderately to strongly bioturbated by 1-4 mm-wide *Chondrites* burrows; fauna consists of brachiopods, bryozoans, and trilobites; contains terrigenous silts less than 1 % in proportion.

(JE10,9,8,7)

JE-4

Dolostone, very fine-crystalline, slightly to moderately argillaceous; 0.5-2 cm-thick wavy argillaceous seams in 5-20 cm intervals; medium gray; weakly bioturbated by 3-8 mm-wide dark gray mottled burrows; fossiliferous mudstone containing brachiopod molds; bounded above by a very prominent hardground.

(JE5,6)

JE-3